BNL-71324-2003
Formal Report

RIKEN BNL Research Center

RBRC/CCAST SYMPOSIUM ON SPIN PHYSICS LATTICE QCD AND RHIC PHYSICS

China Center of Advanced Science and Technology (CCAST) Beijing, China

April 7, 2003

RBRC Scientific Articles

Volume 8

Building 510A, Brookhaven National Laboratory, Upton, N.Y 11973-5000, USA

DISCLAIMER

Available electronically at-

`http://www.doe.gov/bridge`

Available to U.S. Department of Energy and its contractors in paper from-

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
(423) 576-8401

Available to the public from-

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22131
(703) 487-4650

Printed on recycled paper

Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho," (RIKEN) The Institute of Physical and Chemical Research, of Japan. The Center is dedicated to the study of strong interactions, including hard QCD/spin physics, lattice QCD and RHIC (Relativistic Heavy Ion Collider) physics through nurturing of a new generation of young physicists. The Director of RBRC is Professor T. D. Lee.

A Memorandum of Understanding between RIKEN and BNL was signed on April 30, 2002 extending this collaboration and the RIKEN BNL Research Center (RBRC) for another five years.

Since its inception the Center has now matured with both a strong theoretical and experimental group. These consist of Fellows, Postdocs, RBRC Physics/University Fellows and an active group of Consultants/Collaborators. Computing capabilities consist of a 0.6 teraflops parallel processor computer operational since August 1998. It was awarded the Supercomputer 1998 Gordon Bell Prize for price performance. This is expected to be augmented by a ten teraflops QCDOC computer in JFY 2003. The Center also organizes an extensive series of workshops on specific topics in strong interactions with an accompanying series of published proceedings.

Members and participants of RBRC on occasion will develop articles in the nature of a status report, a general review, and/or an overview of special events, such as this one.

N. P. Samios

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98-CH10886.

CONTENTS

RBRC/CCAST Symposium on Spin Physics
Lattice QCD and RHIC Physics
Monday, April 7, 2003
CCAST, Beijing, China

(revised)

<u>Morning</u>	**Chairman: Minghan Ye**	
9:00 a.m.	Welcome	T. D. Lee
	Spin Physics	
9:10 a.m.	Experiments at RHIC, the First Spin Collider	Hideto En'yo
10:00 a.m.	A Discussion on Spin	Gerry Bunce
10:50 a.m.	Tea	
	Chairman: Hideto En'yo	
11:10 a.m.	Using Spin to Explore Nucleon Structure and QCD	Werner Vogelsang
12:00 Noon	Lunch	
<u>Afternoon</u>	**Chairman: Gerry Bunce**	
	RHIC Physics	
1:30 p.m.	RHIC Physics and New Forms of Matter	Larry McLerran
	Lattice QCD	
2:20 p.m.	Fundamental Physics should be based on Difference Equations	T. D. Lee
2:50 p.m.	Domain Wall Fermions and Chiral Symmetry	Taku Izubuchi

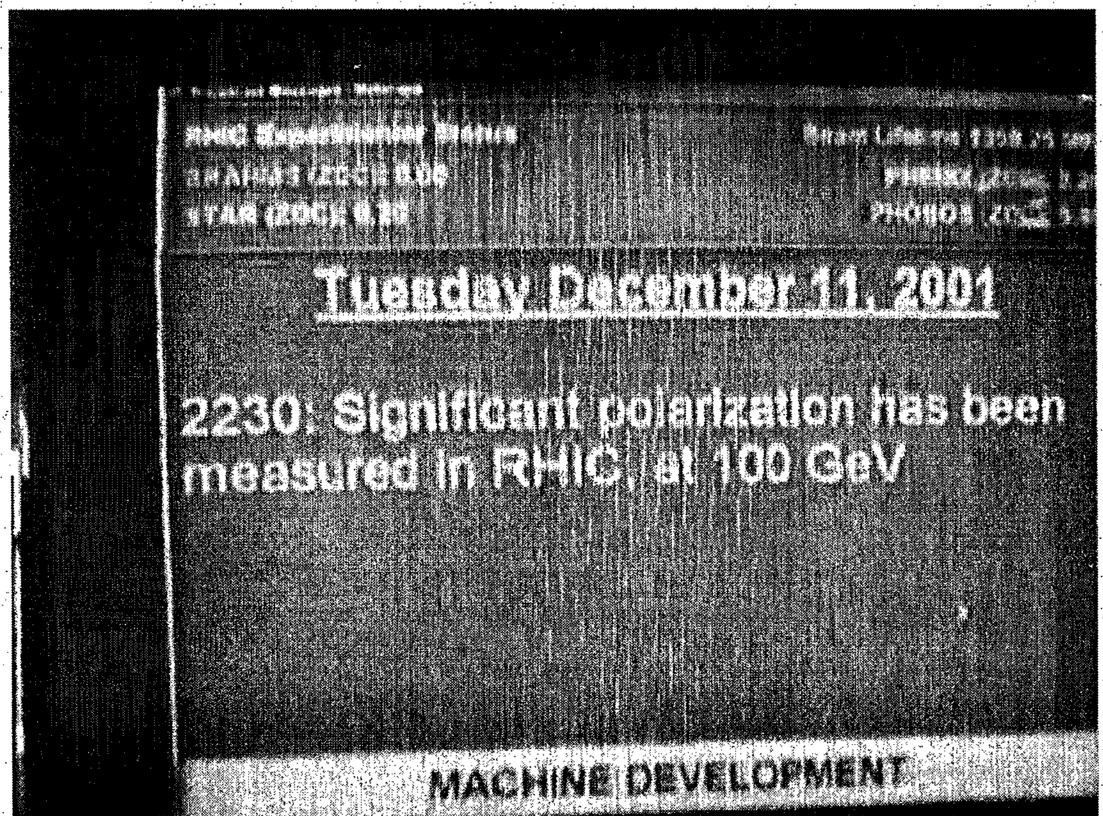
EXPERIMENTS AT RHIC, THE FIRST SPIN COLLIDER

Hideto En'yo
RIKEN, Japan
and
RIKEN BNL Research Center

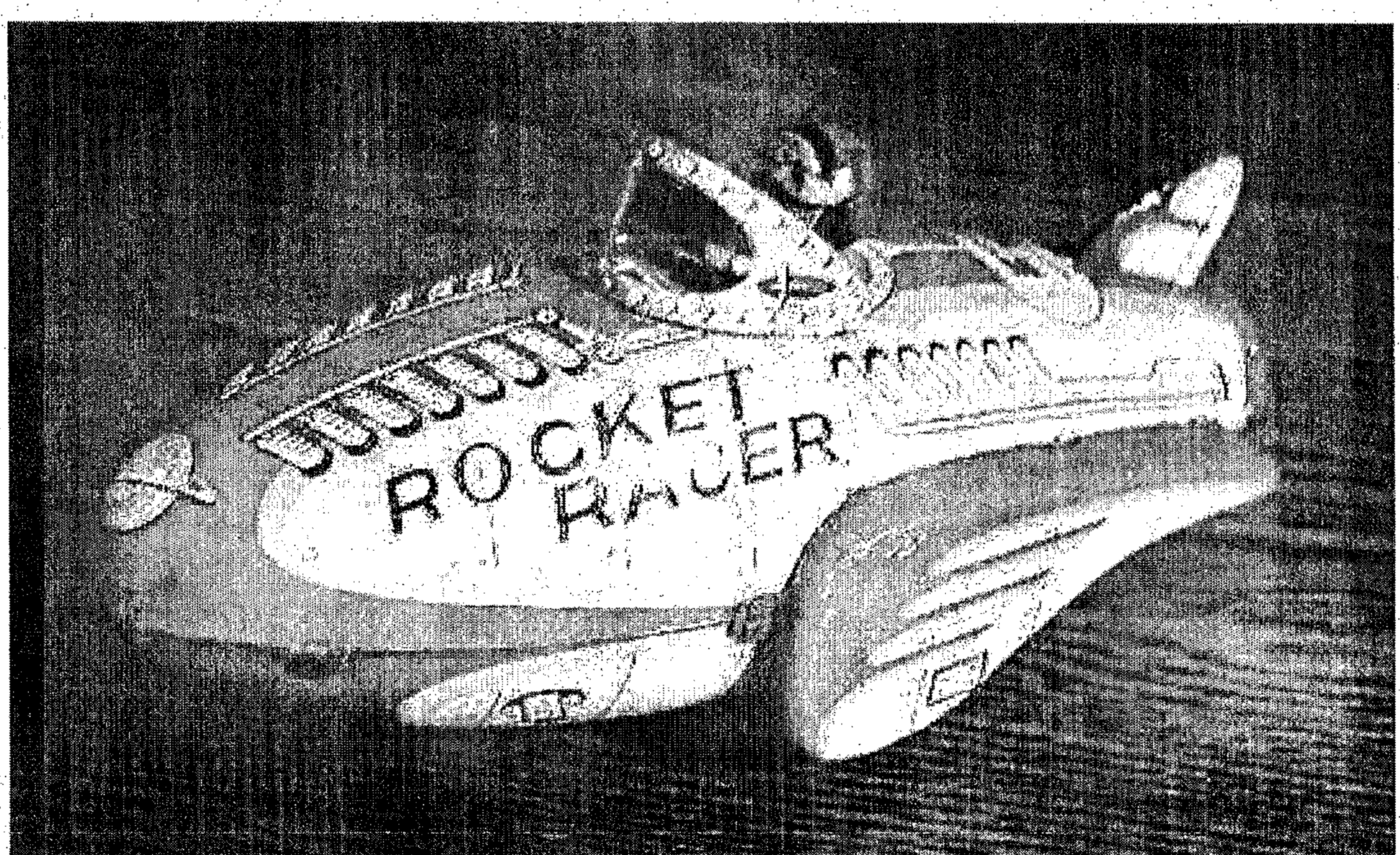
Experiments at RHIC, the First Spin Collider
—— just taking off ——

Hideto En'yo

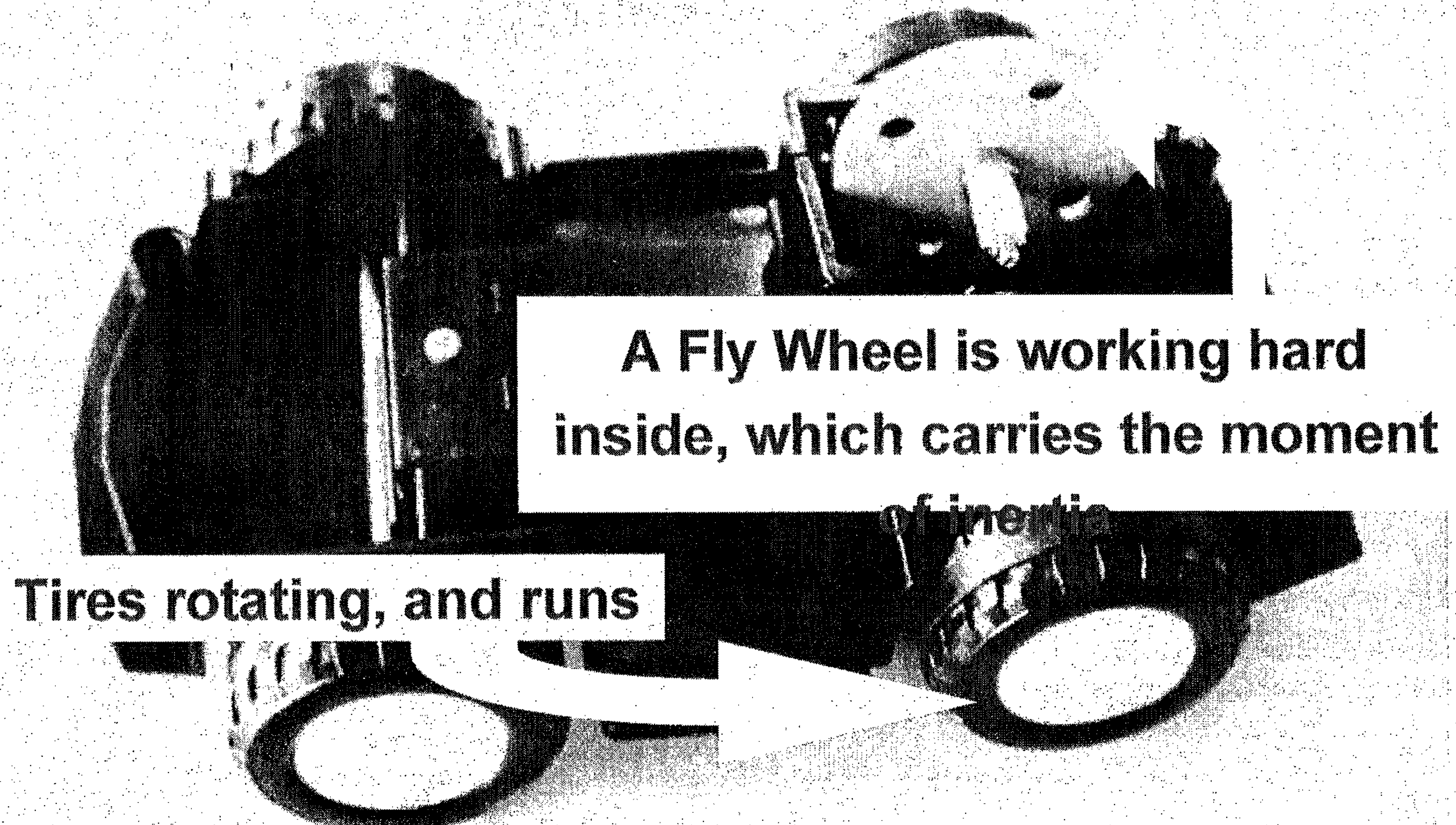
RIKEN / RIKEN-BNL Research Center



Tin Toy

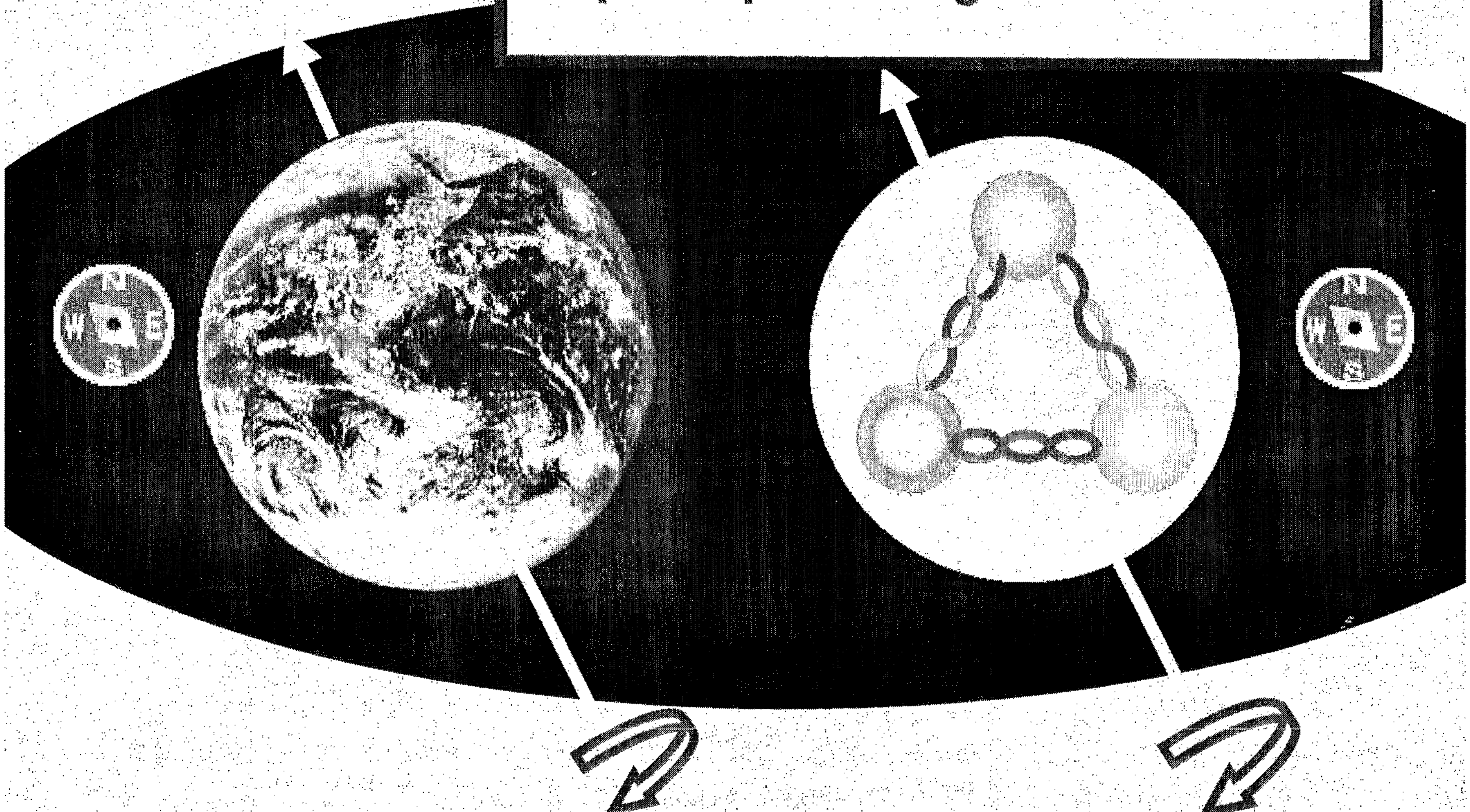


How this toy works ?



Spin of the Earth and Spin of Proton

Spin Top and Magnet characters



Fundamental Questions

What attracts quarks

SOLVED

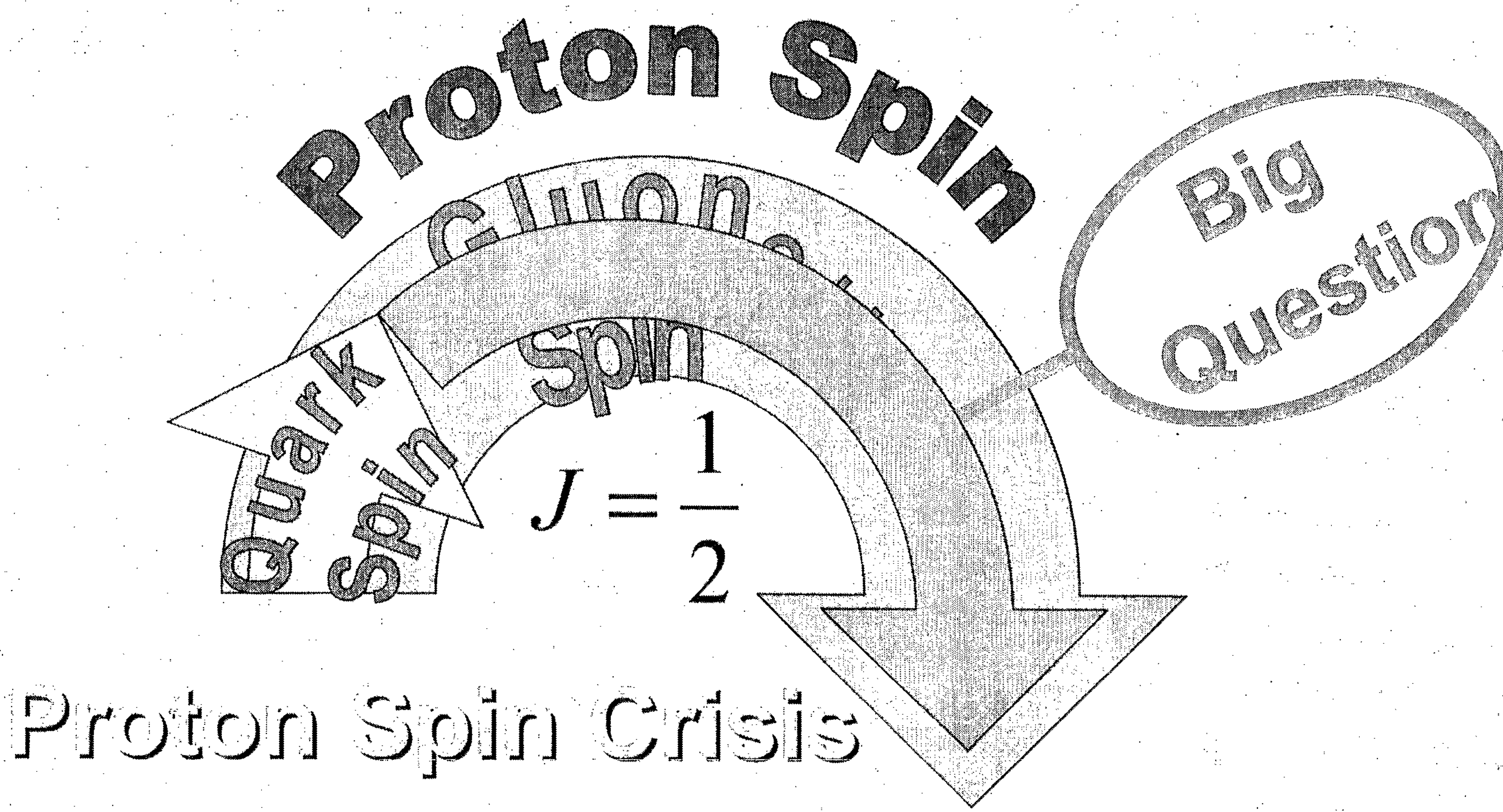
What is the fly wheel of Pro

Big Question

How can we study ?

Facility Read

What is the fly wheel in the proton



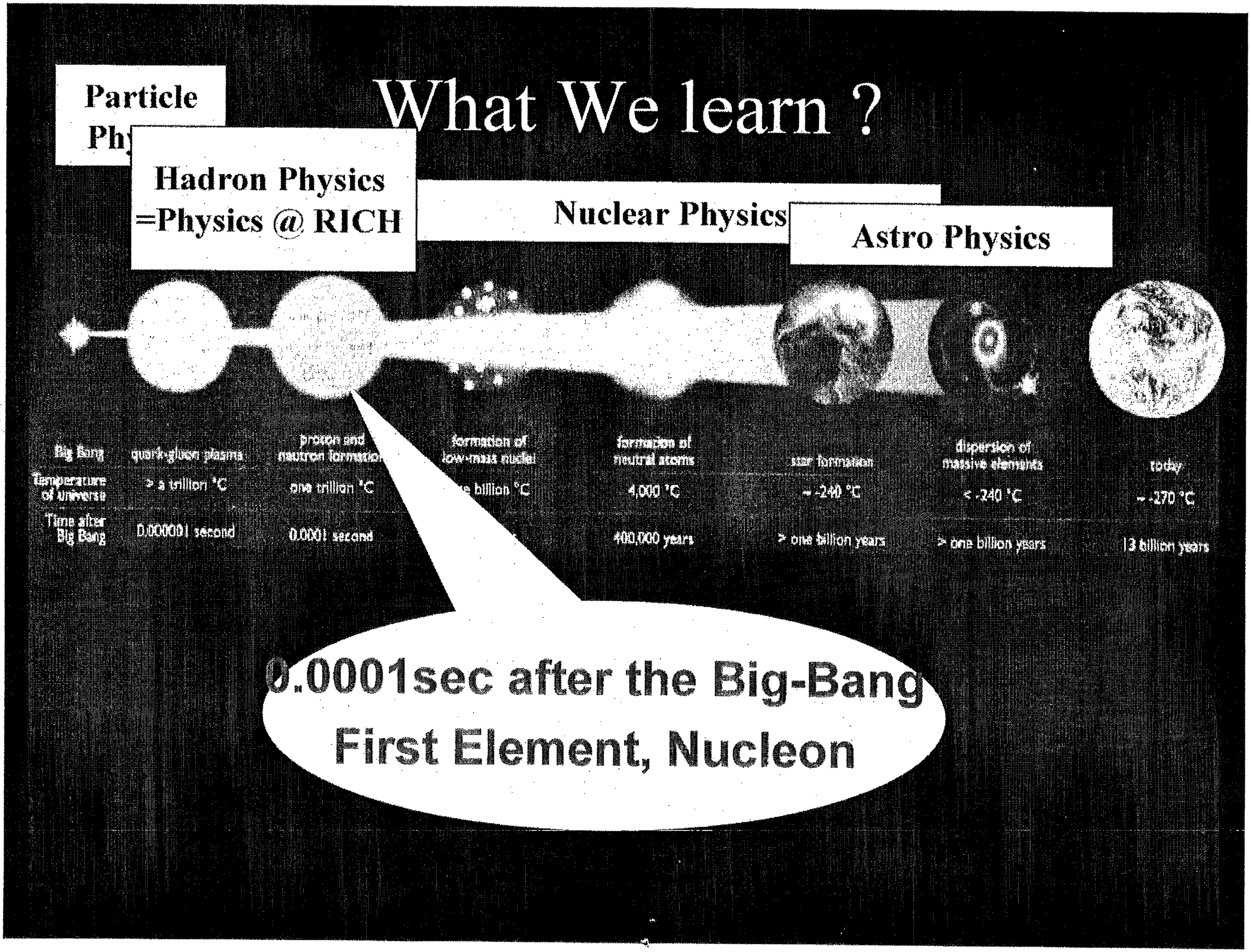
Polarize protons (arrange all the proton spin to the same axis)

Accelerate to the very high energy

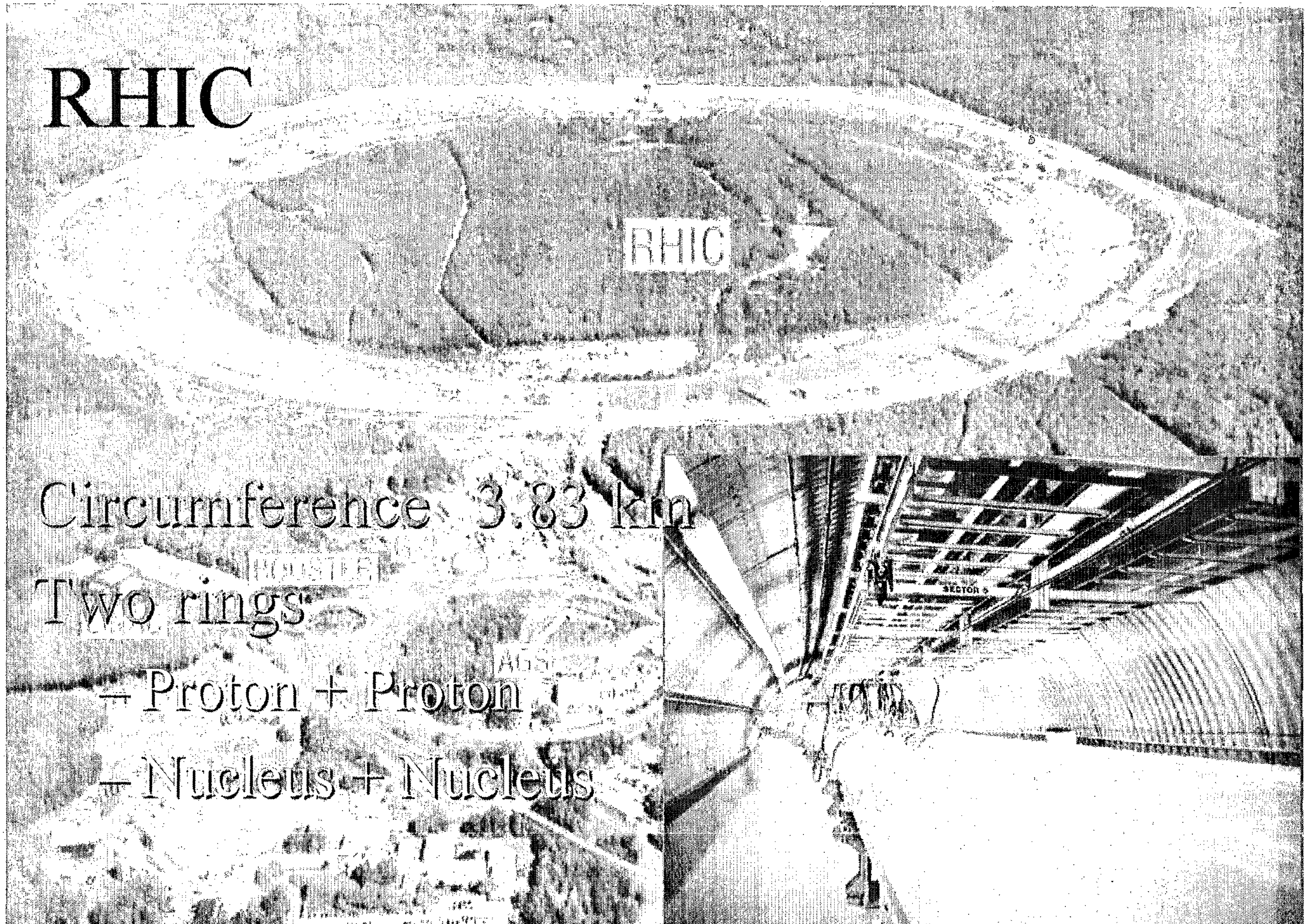
And Collide !

Spin collider

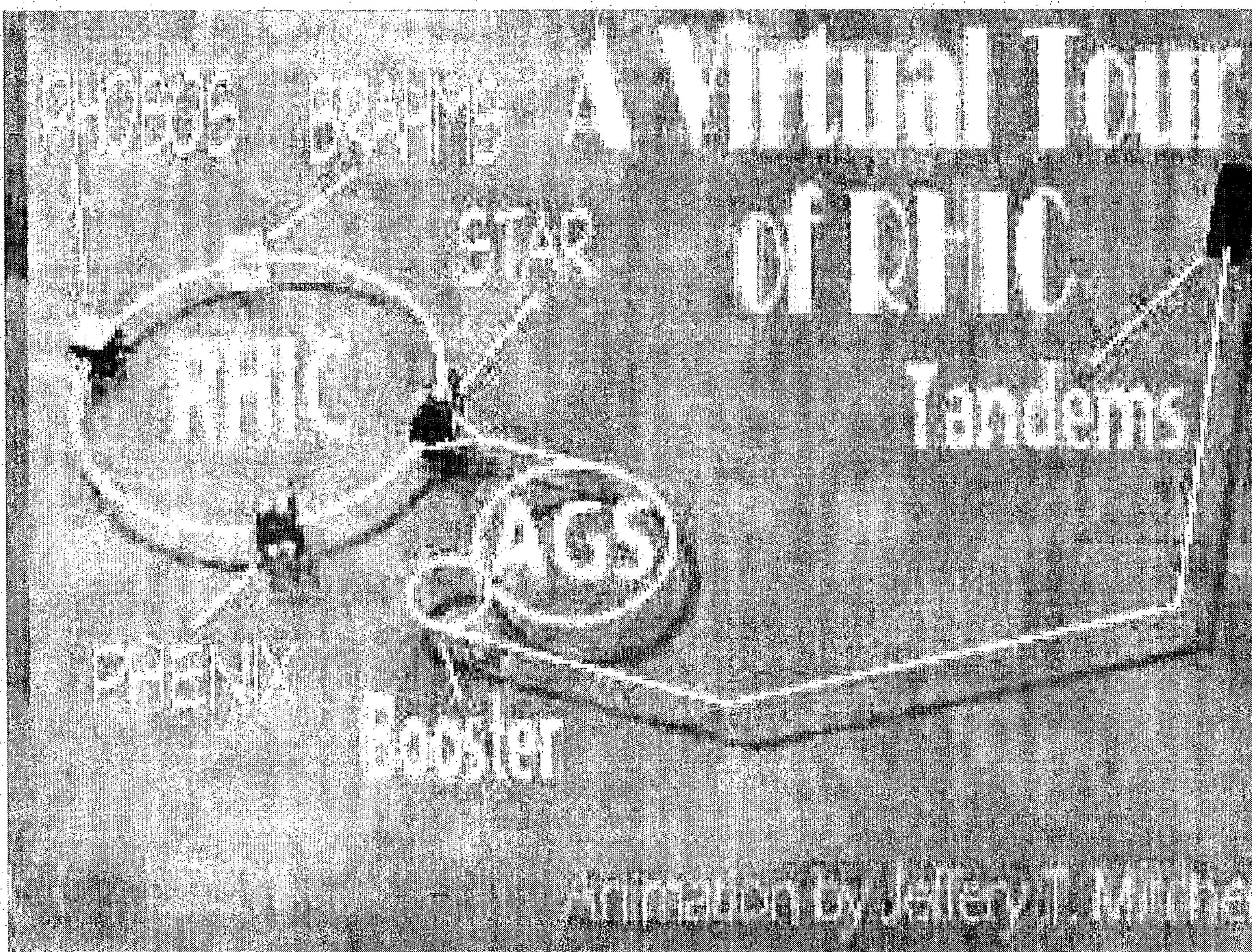
【The first in the world】


What We learn ?
Particle
Hadron Physics
=Physics @ RICH
Nuclear Physics
Astro Physics
Big Bang
quark-gluon plasma
proton and
formation of
low-mass nuclei
formation of
neutral atoms
star formation
dispersion of
massive elements
today
Temperature of universe
> a trillion °C
one trillion °C
4,000 °C
~ -240 °C
< -240 °C
~ -270 °C
Time after Big Bang
0.000001 second
0.0001 second
400,000 years
> one billion years
> one billion years
13 billion years
0.0001sec after the Big-Bang
First Element, Nucleon

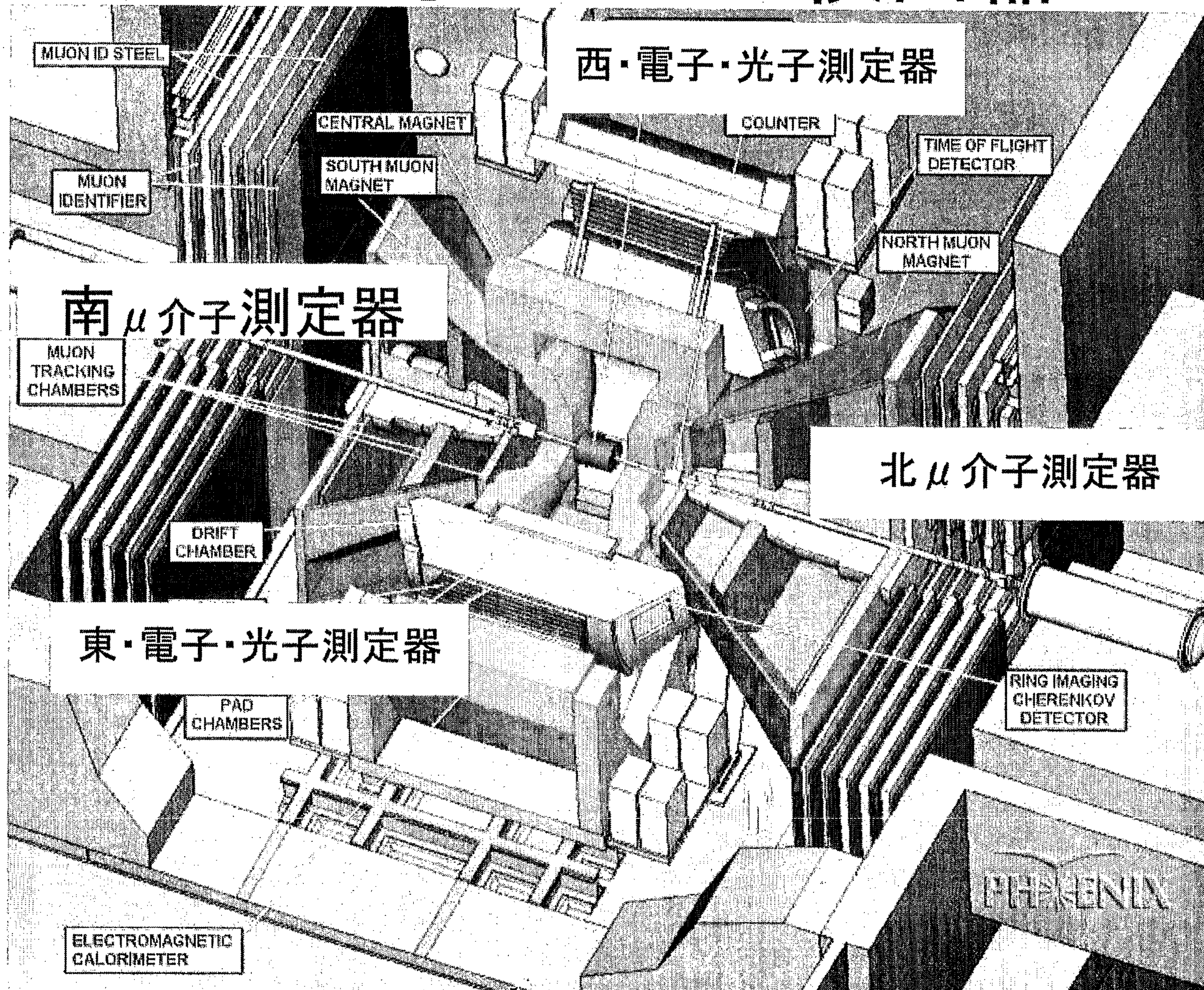
Long Island, USA、NY



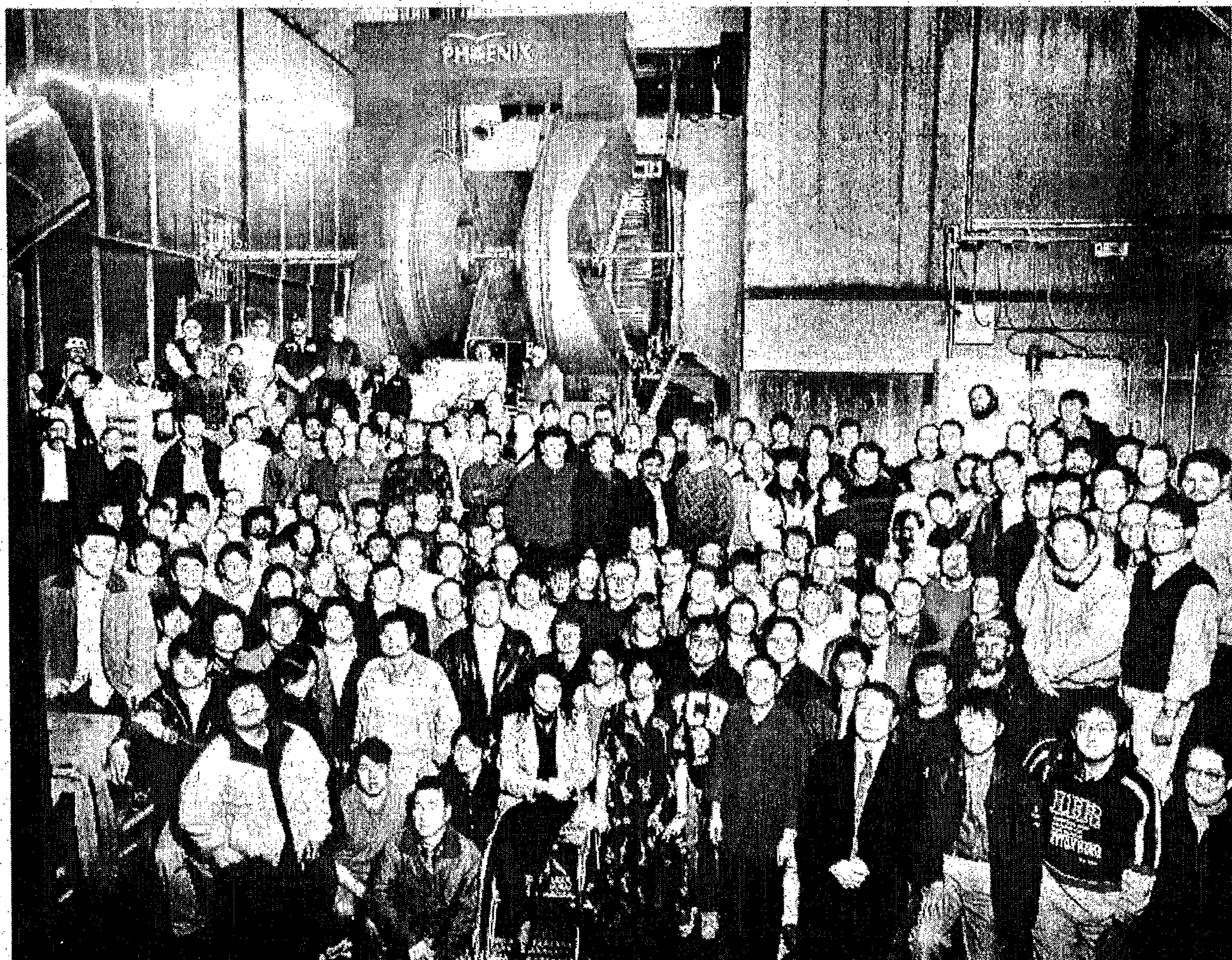
RHIC
RHIC
Circumference 3.83 km
Two rings
– Proton + Proton
– Nucleus + Nucleus
BOOSTER
AGS
SECTOR 5

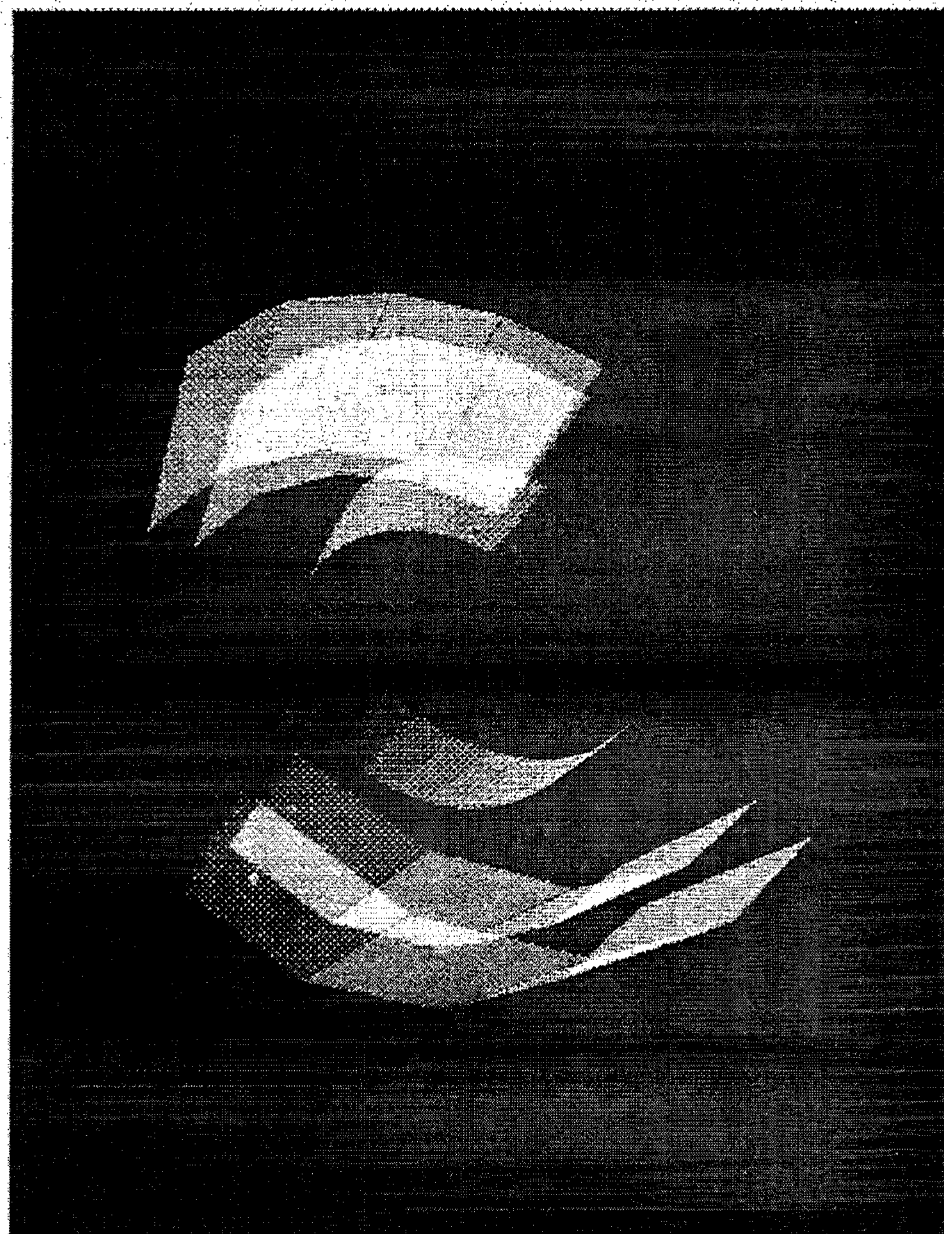

A Virtual Tour
of RHIC
PHOBOS
BRAHMS
STAR
RHIC
Tandems
AGS
PHENIX
Booster
Animation By Jeffery T. Mitchell

不死鳥PHENIX 検出器

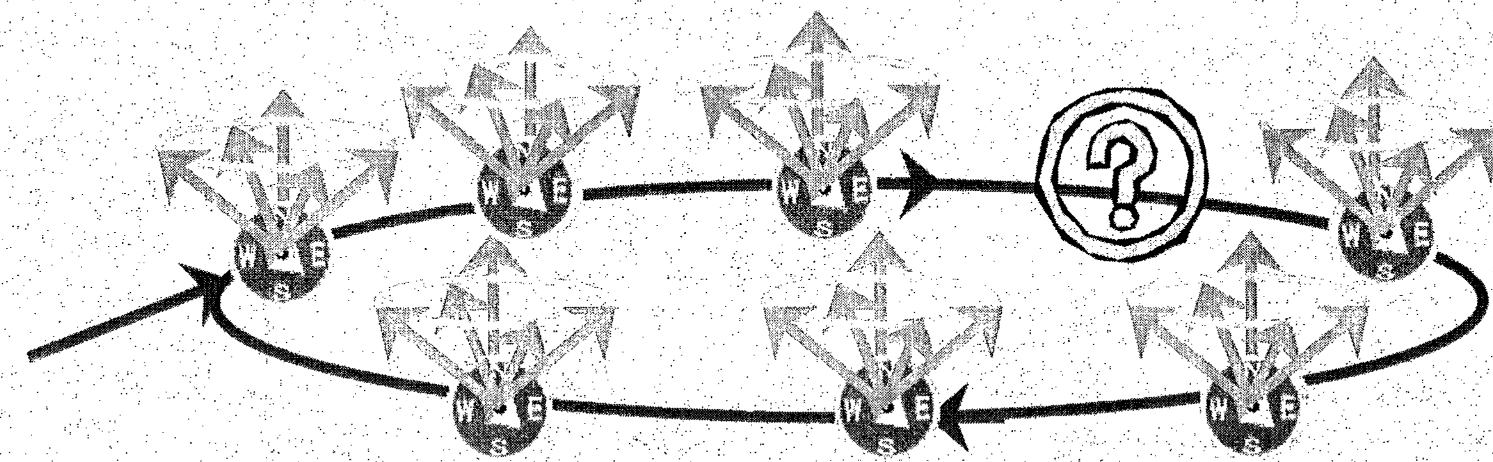


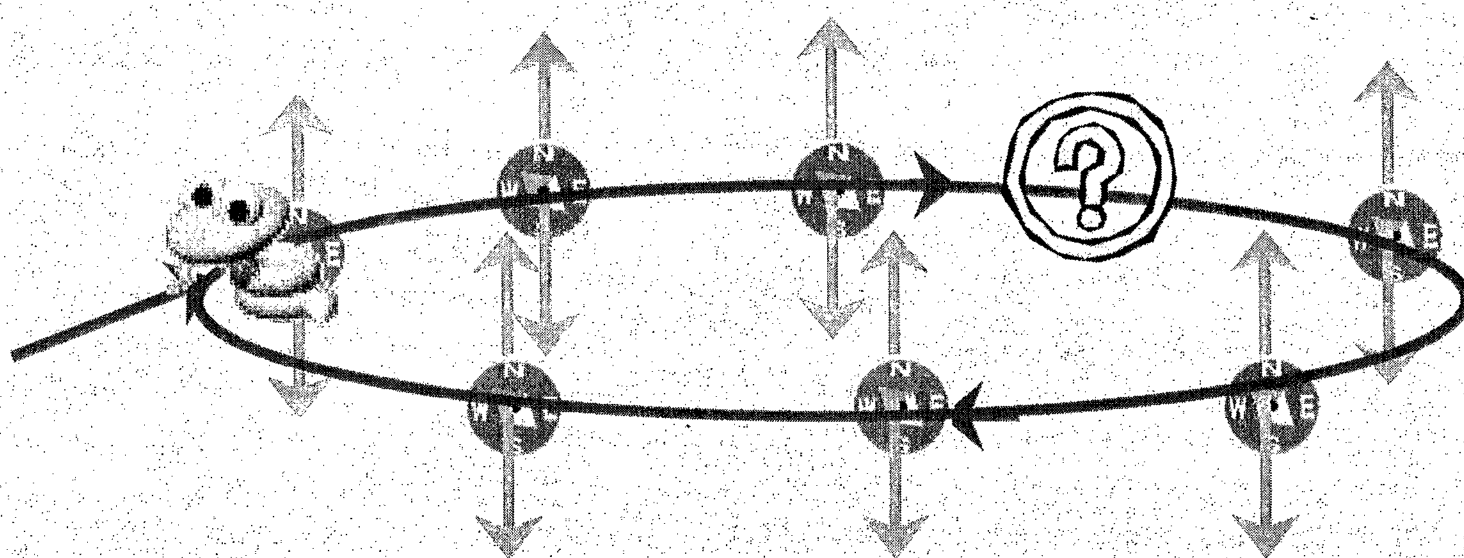
PHENIX Experiment



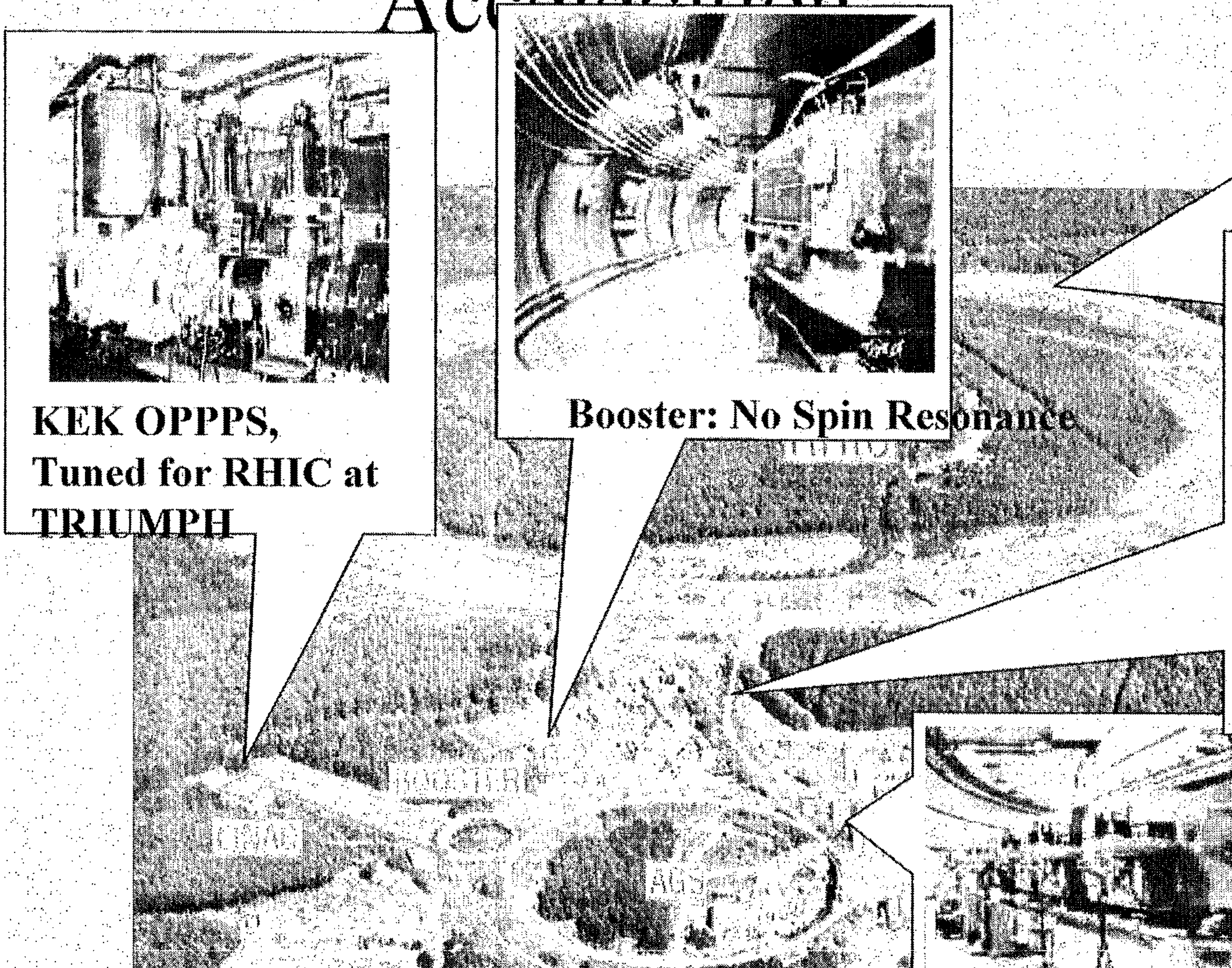


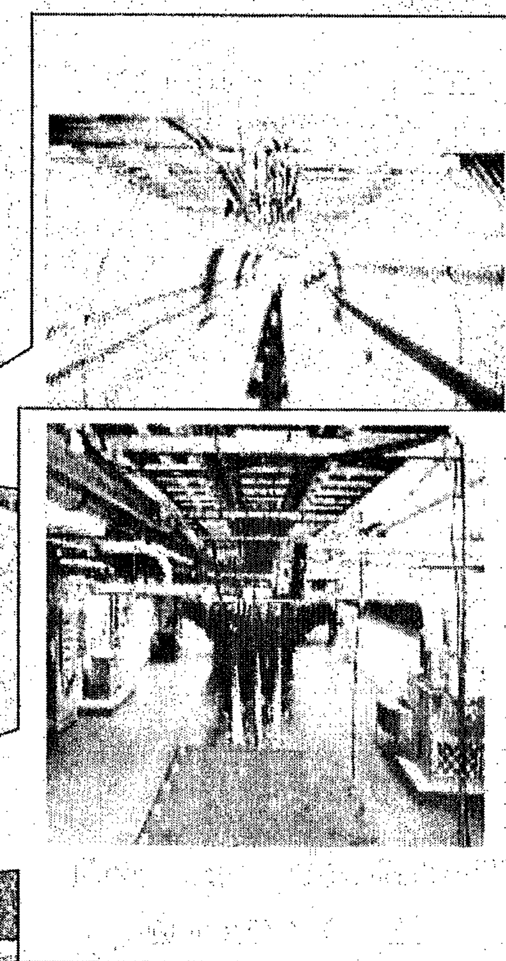
How we can polarized proton spin

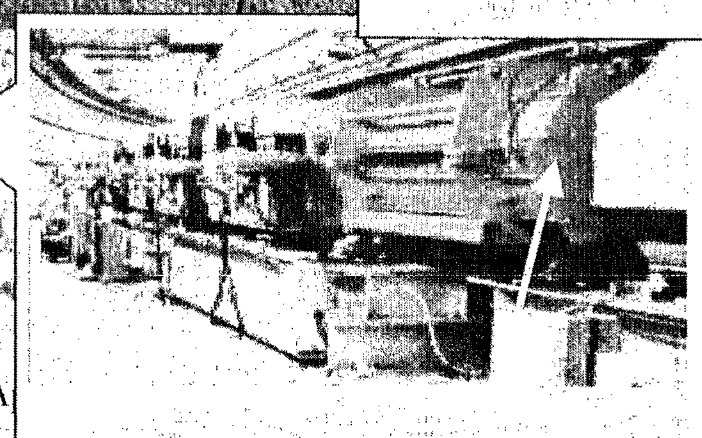




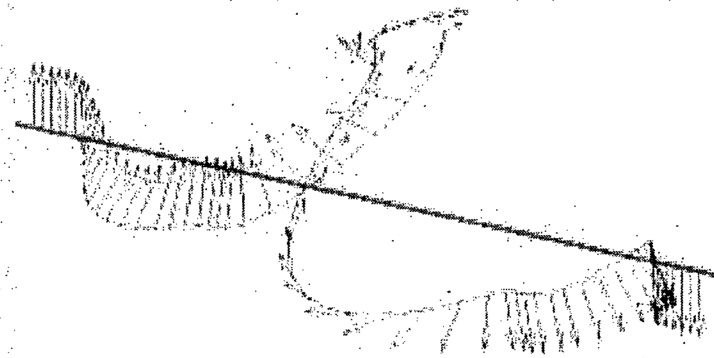
Polarized Proton Acceleration







Snake Magnet

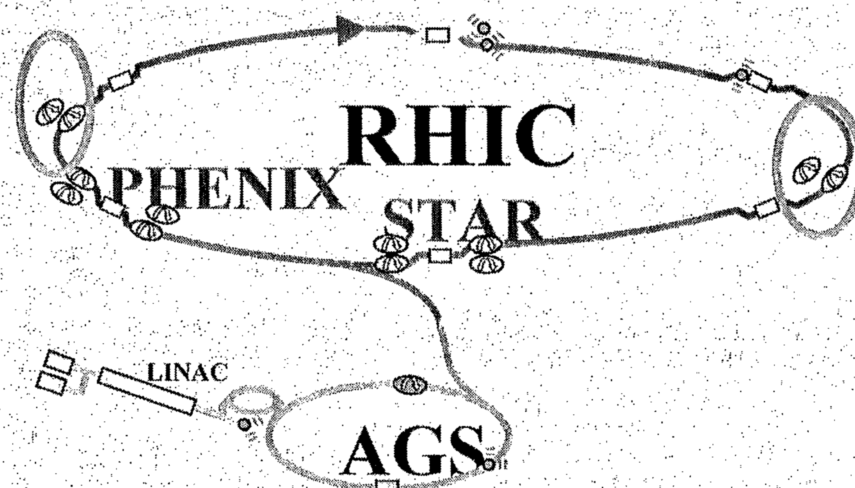


Proton and its spin motion in Snake

4 Helical Dipoles – one Snake
essential invention for RHIC spin

2 Snakes in each ring
Snake axis orthogonal each other
Spin is preserved up to 250GeV

RIKEN fund



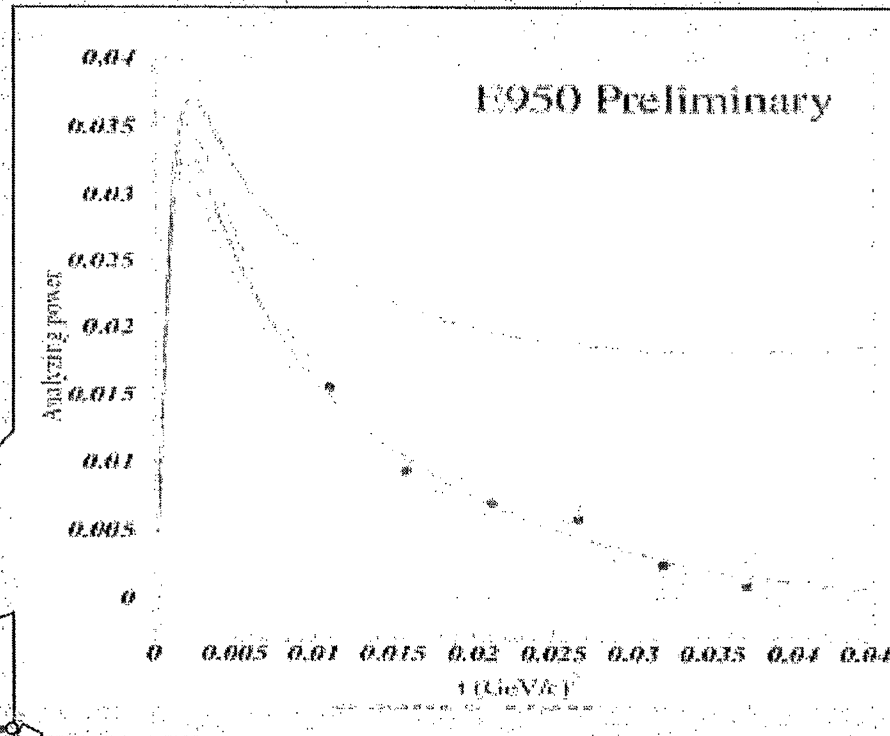
PaNic02 K.Kurita

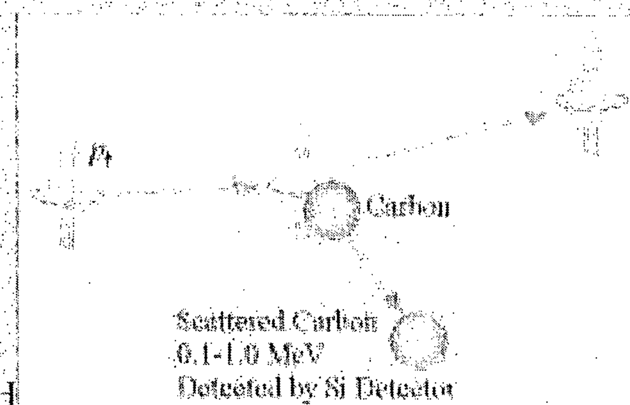
Coulomb Nuclear Interference Polarimeter

- Carbon filament target ($5 mg/cm^2$) in the RHIC beam
- Measure recoil carbon ions at $\theta \sim 90°$
- $100\ keV < E_{carbon} < 1\ MeV$

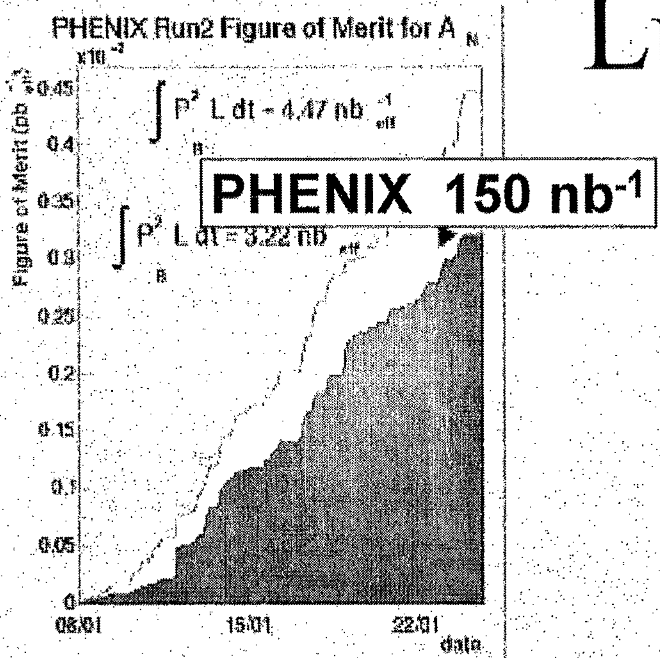
Wave-Form Digitizer +FPGA

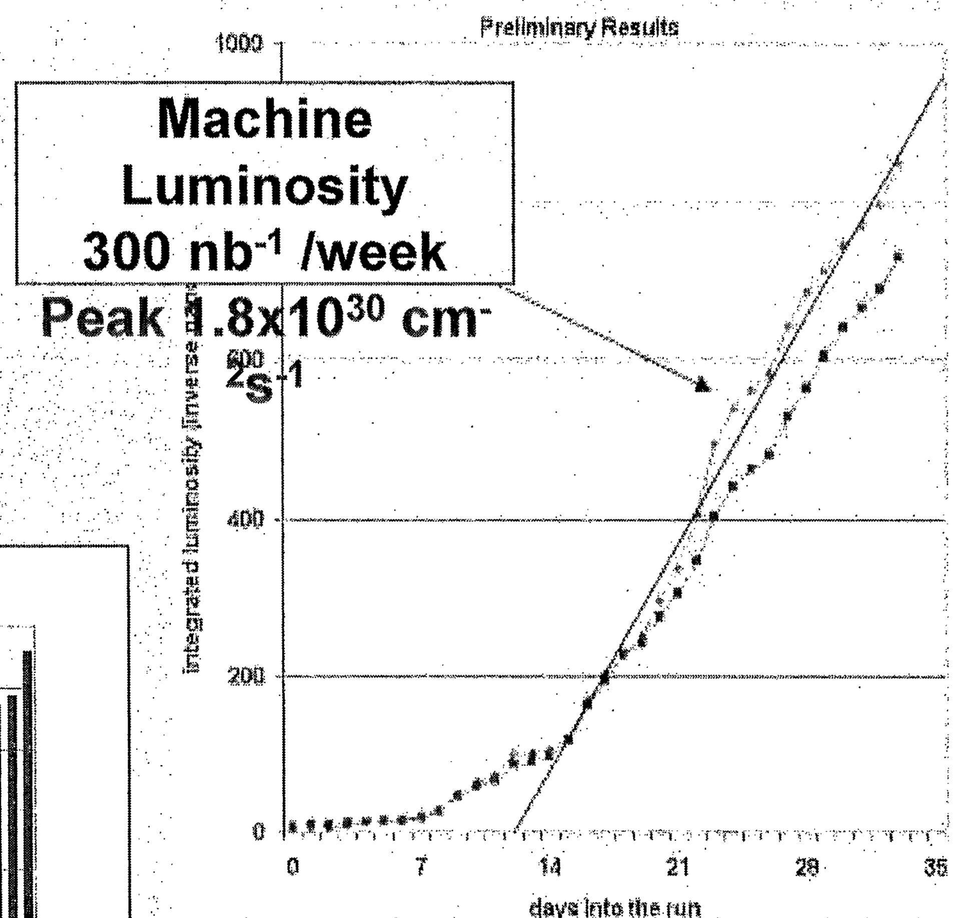
- high counting rates (~0.5 MHz) scaler measurement $\Rightarrow \delta\varepsilon \sim 3\times10^{-4}$ in ~1 minute.

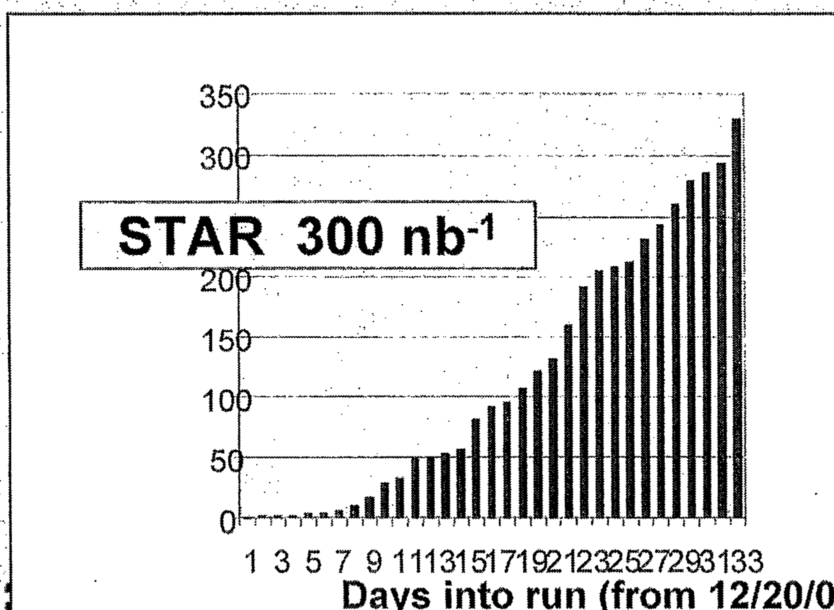




Luminosity in Year 1

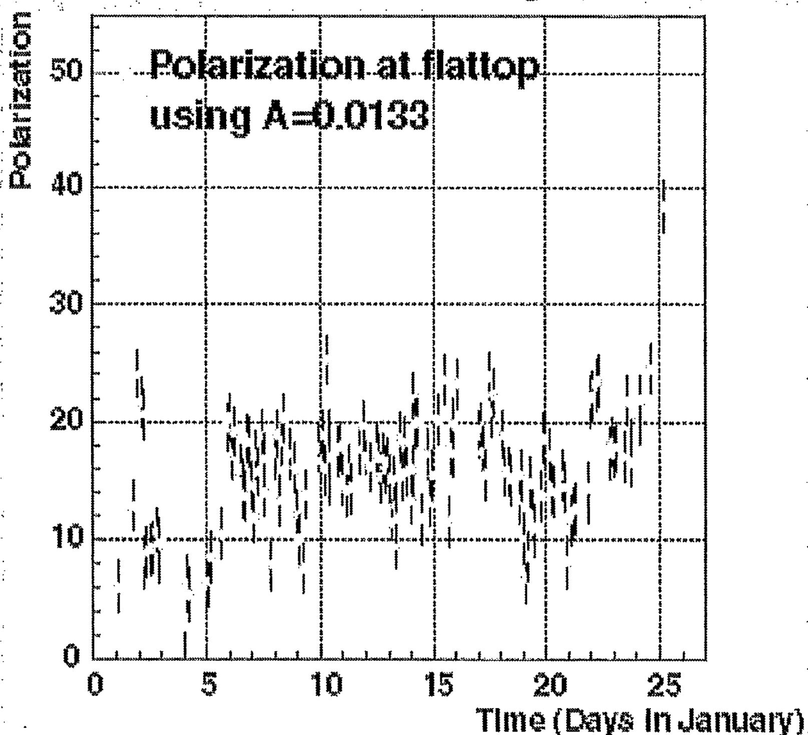




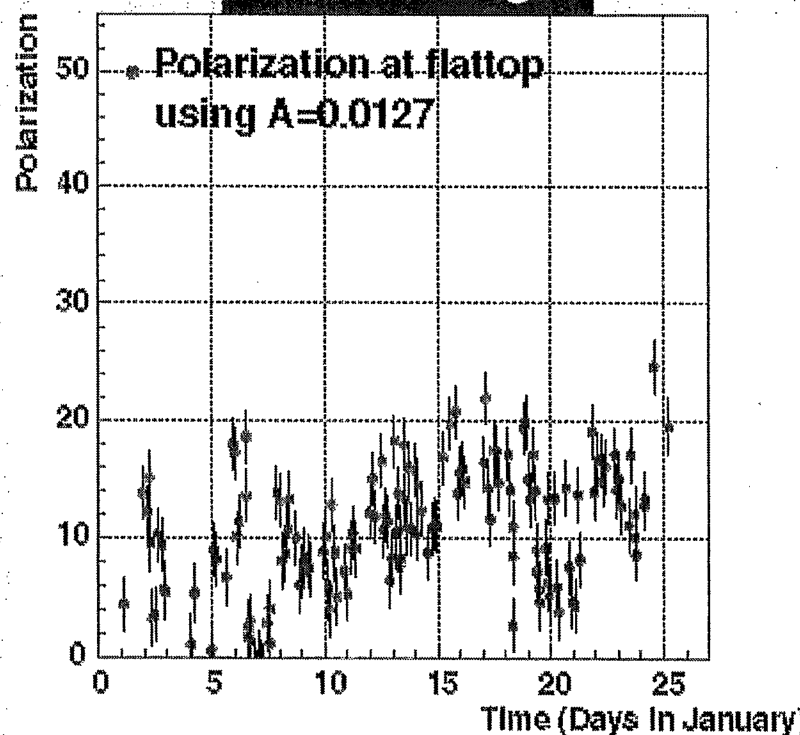


Polarization in Year 1

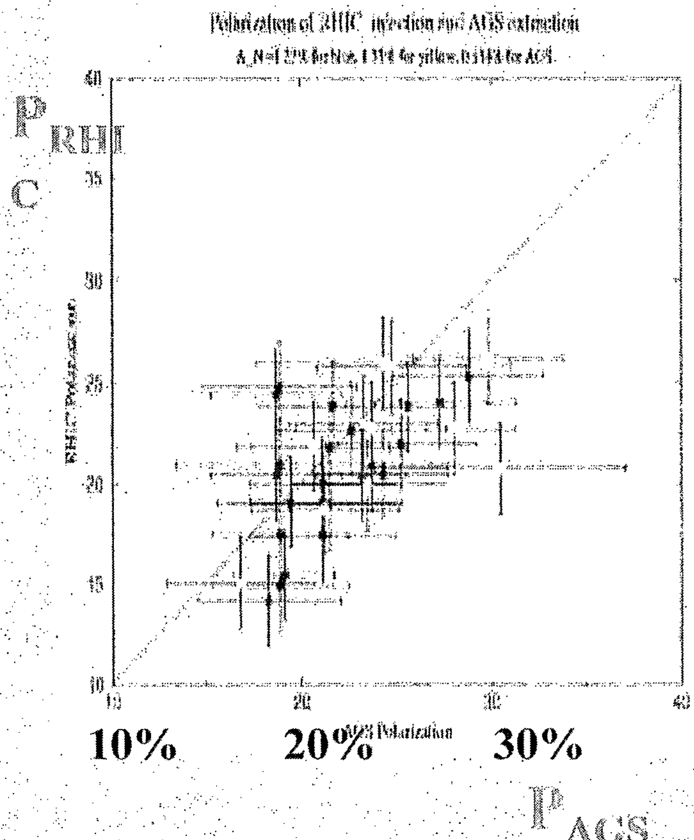
Yellow Ring

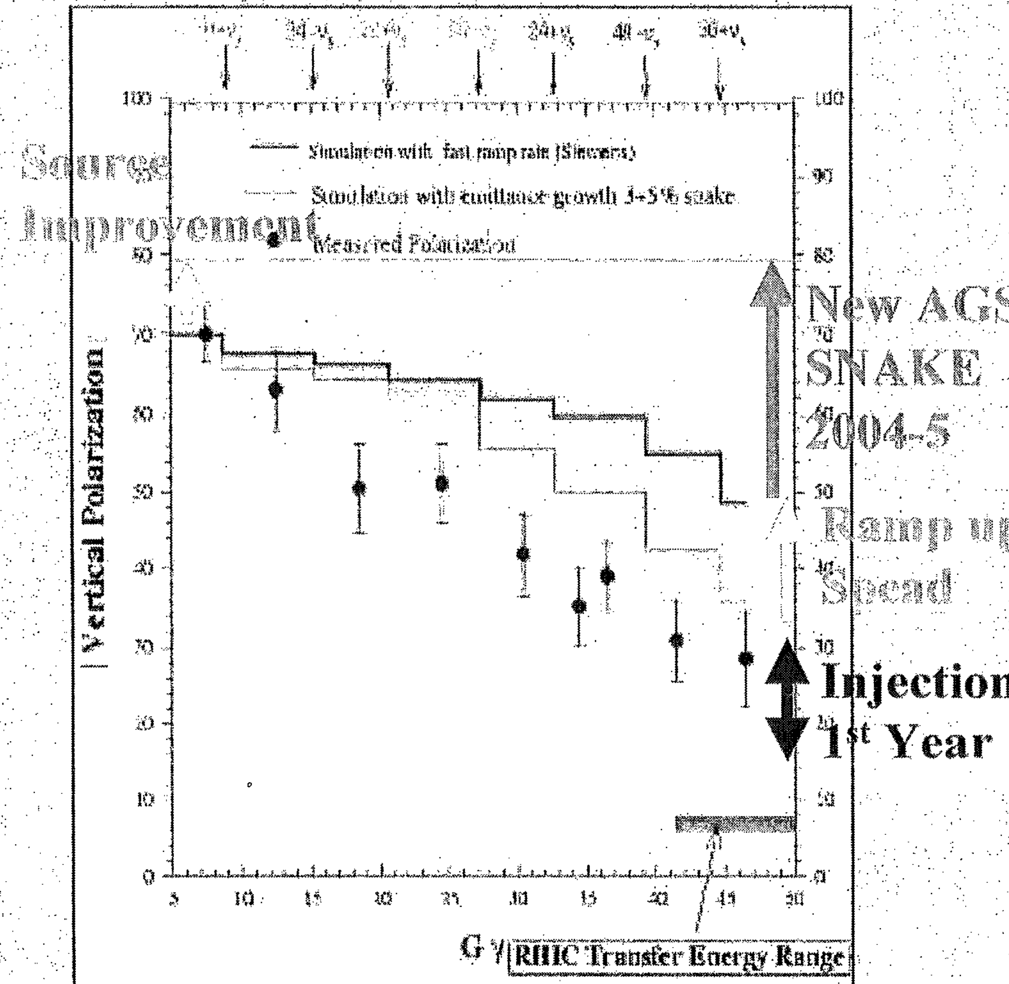


Blue Ring



Why polarization was low ?



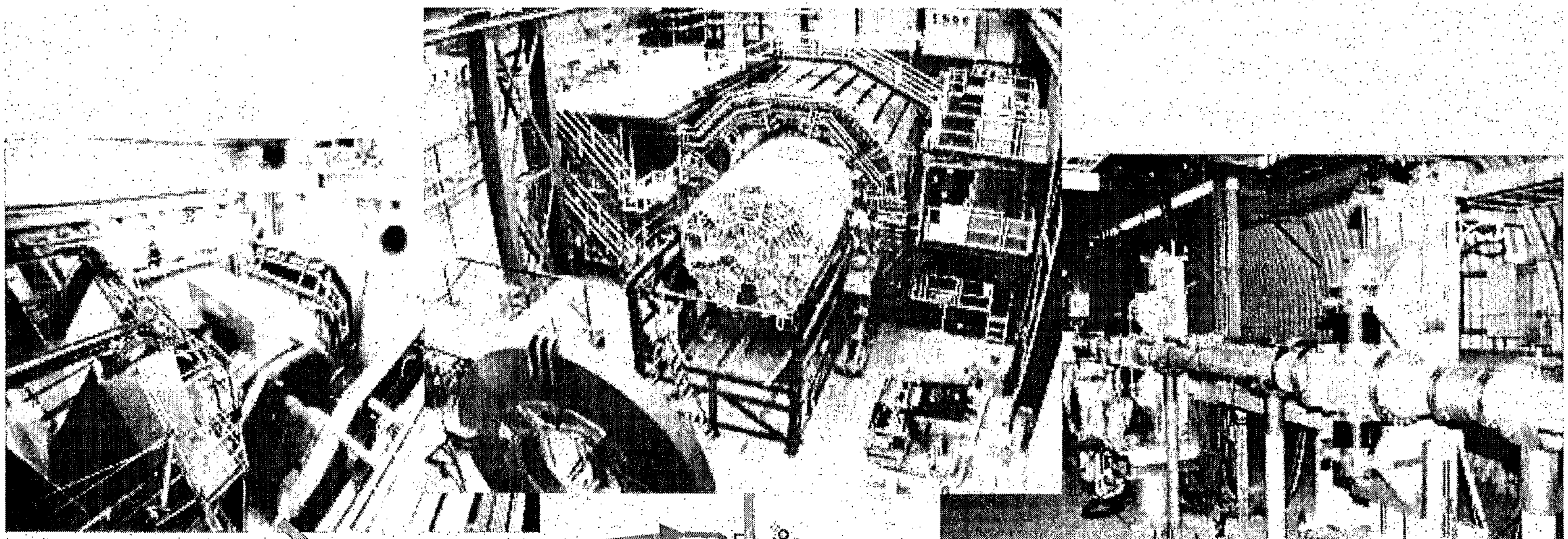


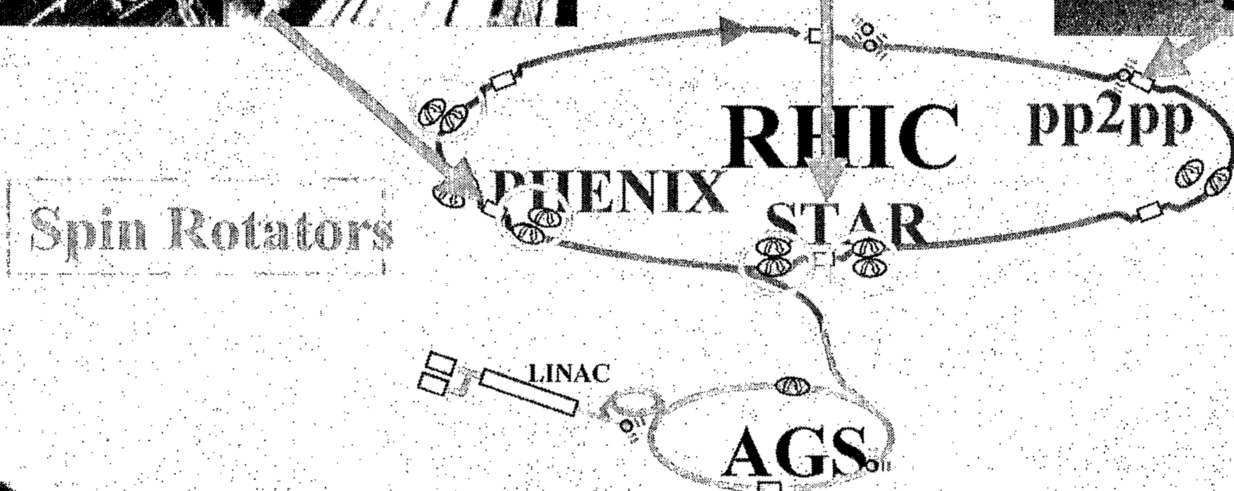
AGS motor generator failure
½ ramp up speed
2x resonance effect

Prospect of Machine performance

RUN	#proton /bunch [$\times 10^9$]	#bunch	Beta* (m)	Emittance ($\pi\mu$m)	Luminosity 10^{30} $cm^{-2}s^{-1}$	Pol. (%)
2001-2002	70	55	3	25	1.8	15-25
2002-2003	100	112	1	25	16	45-55
2005-	?	112	1	?	?	70-80
Design	200	112	1	20	80	70

The Spin Experiments





pp elastic
Silicons in Roman pot
-t down (0.004 GeV/c)^2
b*=10m (special tune)

Spin Physics at RHIC

RHIC = polarized parton collider

- Spin Structure of Nucleon
  - $1/2=(1/2)\Delta\Sigma+\Delta G+L_q+L_g$

    ΔG: gluon polarization

    $\Delta\bar{q}$: Anti-quark polarization
  - New Structures
    - h_1: transversity

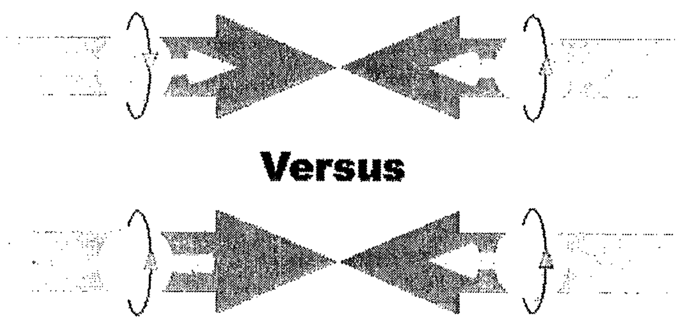
- Test of pQCD
  - Use asymmetries sensitive ONLY to the higher orders (A_N at high P_T etc.)

- NEW TOOL to study hadronic processes
  - W,Z @500GeV
    - flavor sensitive studies
    - on the structure functions
  - cc/bb
    - Production mechanism
  - Spin in the fragmentation

?QCD triumph?
or
?beyond ?

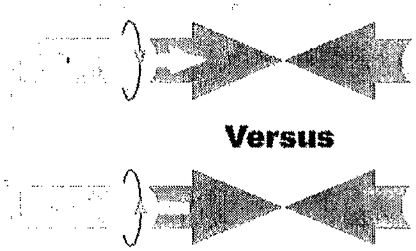
Asymmetries Measurements

- A_{LL}: Double Longitudinal Spin Asymmetry
  - Useful in extracting quark distributions

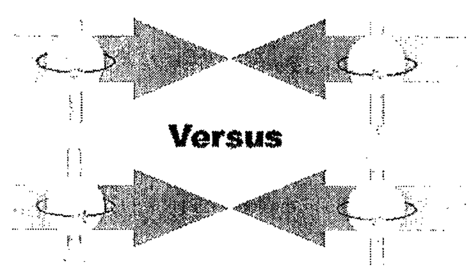


$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$

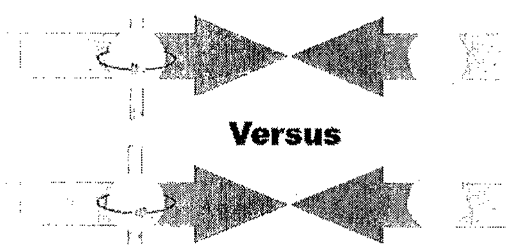
A_L:Parity Violation



A_{TT}: Transversity



A_N:Twist-3 or $\cancel{T}$

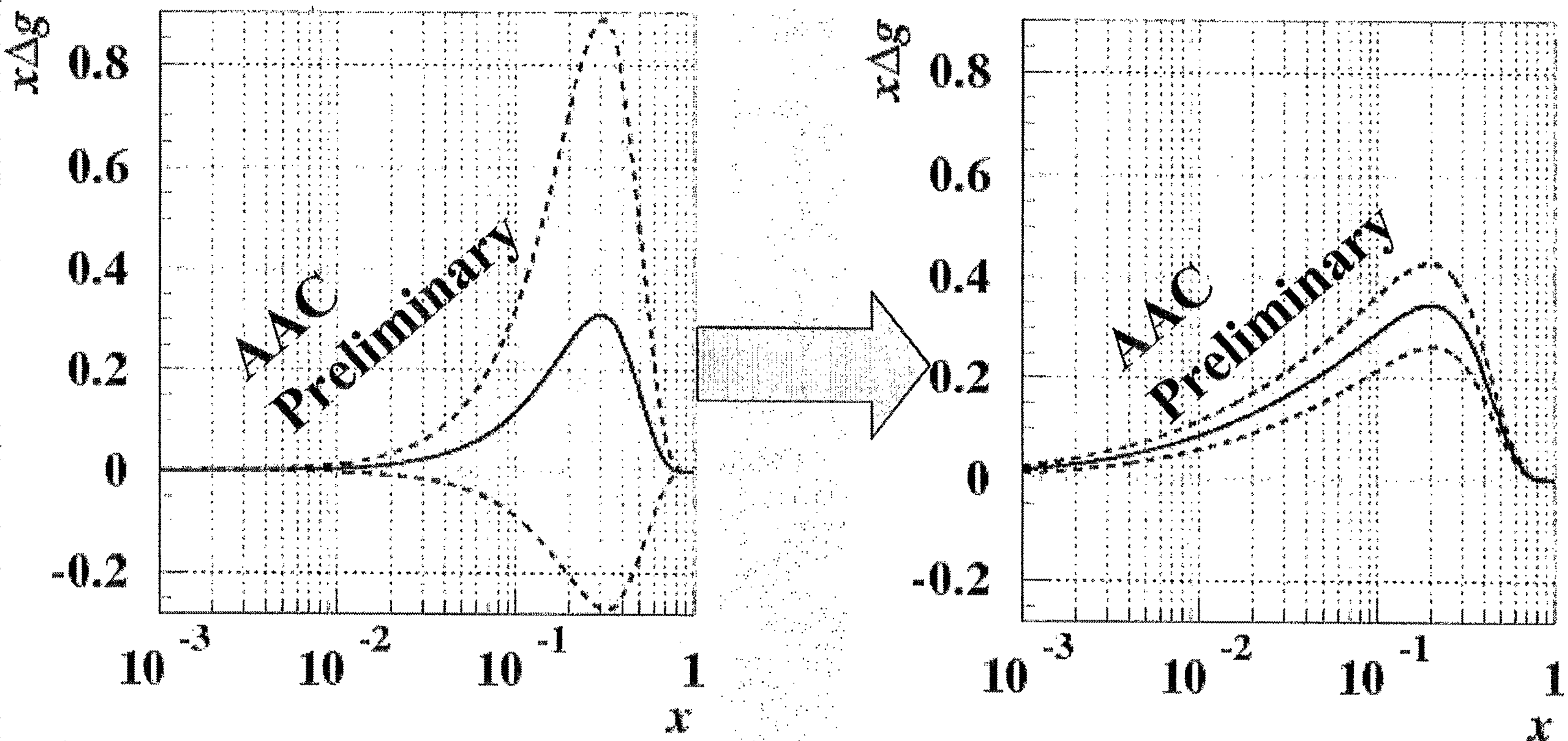


RIKEN

Impact of RHIC Spin on Δg

Global QCD Analysis

With RHIC DATA (1year)



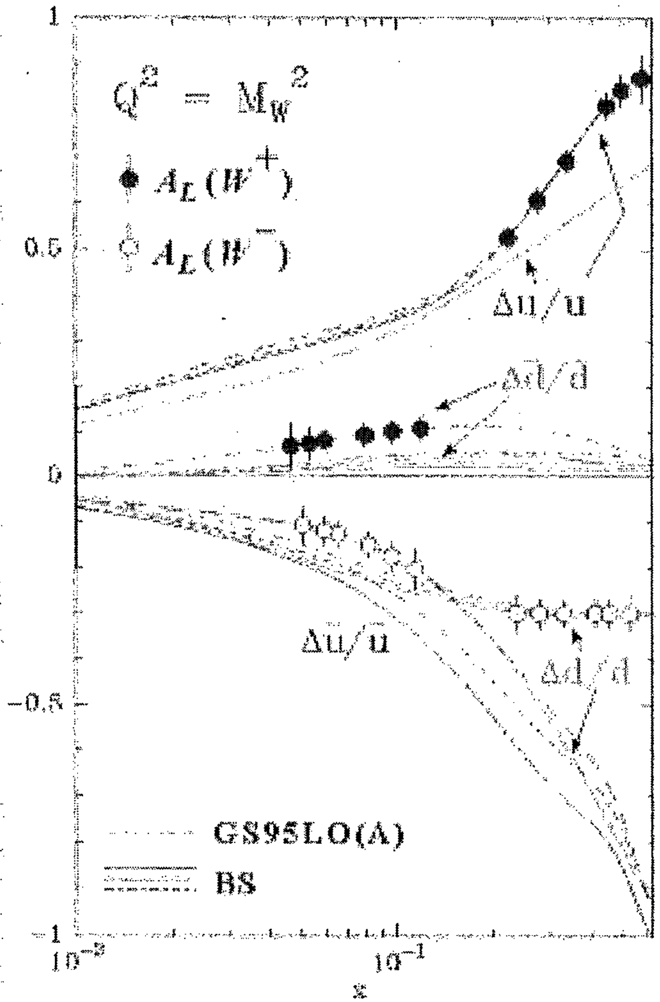
M. Hirai, H.Kobayashi, M. Miyama *et al.*

Measurements of $\Delta\bar{q}$, Δq at PHENIX

Parity violating single Asymmetry

unpolarized distribution × polarized distribution

$$A_L^{W^+} = \frac{\Delta u(x_a, M_W^2)\bar{d}(x_b, M_W^2) - \Delta\bar{d}(x_a, M_W^2)u(x_b, M_W^2)}{u(x_a, M_W^2)\bar{d}(x_b, M_W^2) + \bar{d}(x_a, M_W^2)u(x_b, M_W^2)}$$



– $\bar{d}$ small at high x → $\Delta u/u$ ($\Delta d/d$ for W^-)
flavor selected valence quark polarization
→ $\Delta \bar{d}/\bar{d}$ ($\Delta \bar{u}/\bar{u}$ for W^-) determination

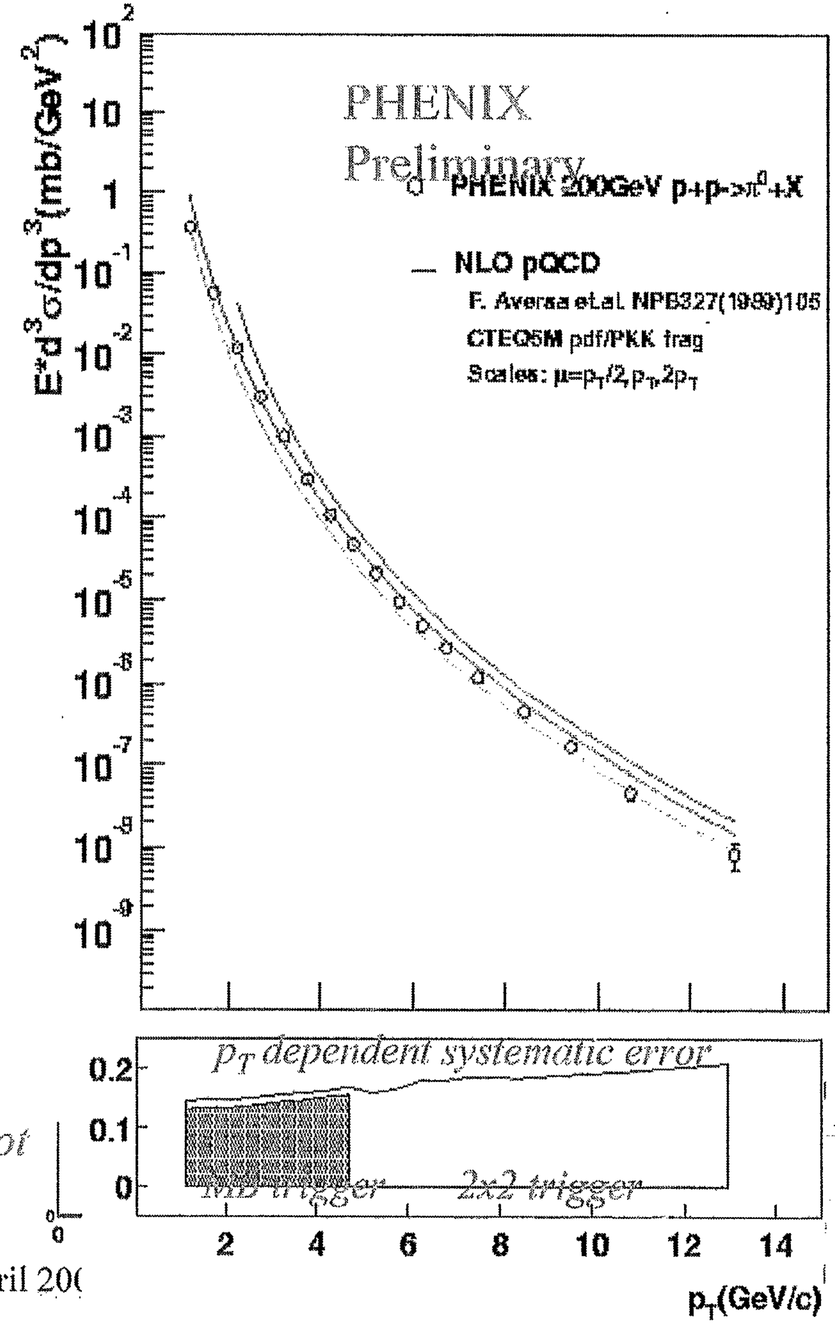
Major background is Z decay (20%)

systematic error will be minimized (~1%) with A_L^Z (~20%) and $\sigma(Z)$ measurements

Spin02 B.Fox (RBRC)
QM02 H,Torii(Kyoto)
PaNic02 Y. Goto(RIKEN)

PHENEIX
π^0 cross section

- Pt Spectrum over 10^8 magnitude
- NLO pQCD calculation
  - CTEQ5M pdf
  - Potter-Kniehl-Kramer(PKK)
  - fragmentation function
  - $\mu = p_T/2, p_T, 2p_T$
- Consistent with data within the scale dependence.



Normalization error of 30% not shown.

32

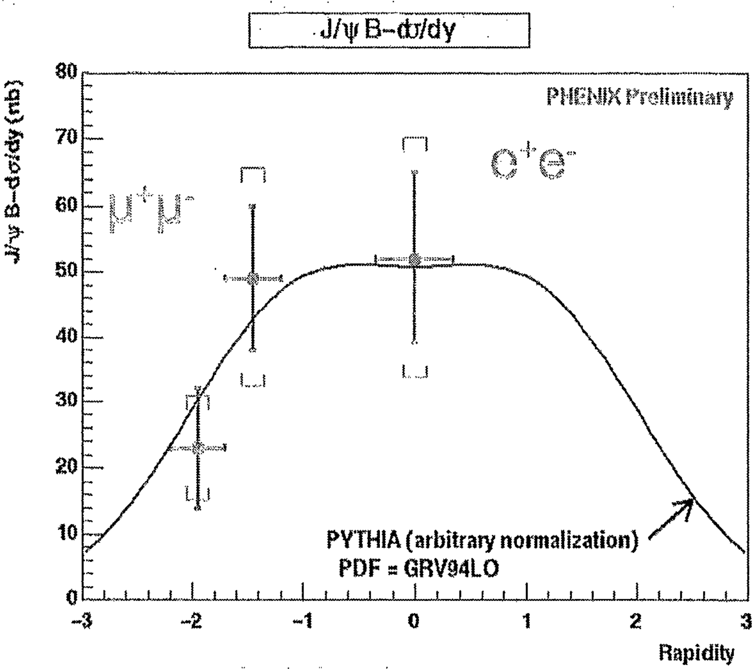
RIKEN

Spin02 H.
Sato(Kyoto) Panic02
K.Ozawa(CNS)

PHENIX J/ψ

33

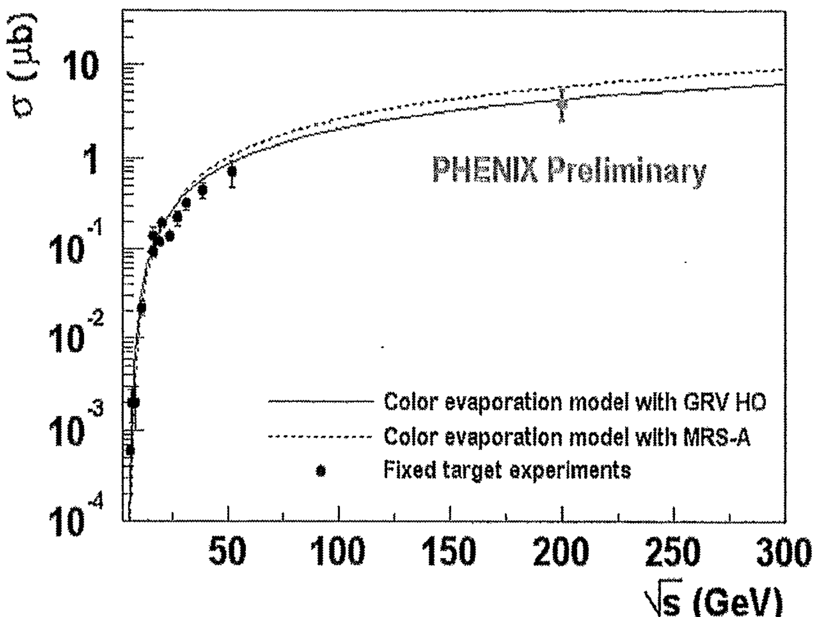
Rapidity distribution compared with PHITHIA simulation



$Br(J/\psi \to l^+l^-)\ \sigma(total) = 226 \pm 36\ (stat.) \pm 79\ (syst.)$ nb
$\sigma\ (p+p \to J/\psi X) = 3.8 \pm 0.6\ (stat.) \pm 1.3\ (syst.)$ μb

PHENIX Preliminary

Total Cross section vs. the Color-Evaporation Model prediction

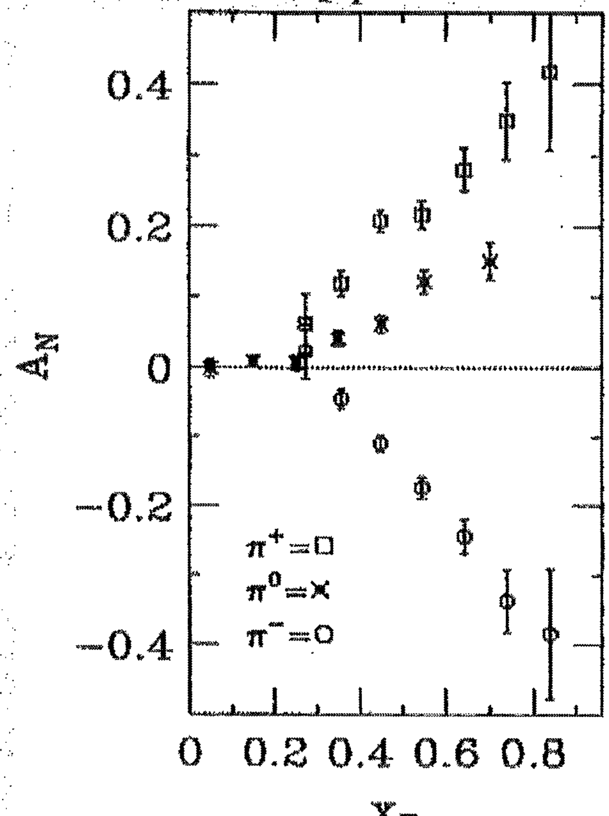


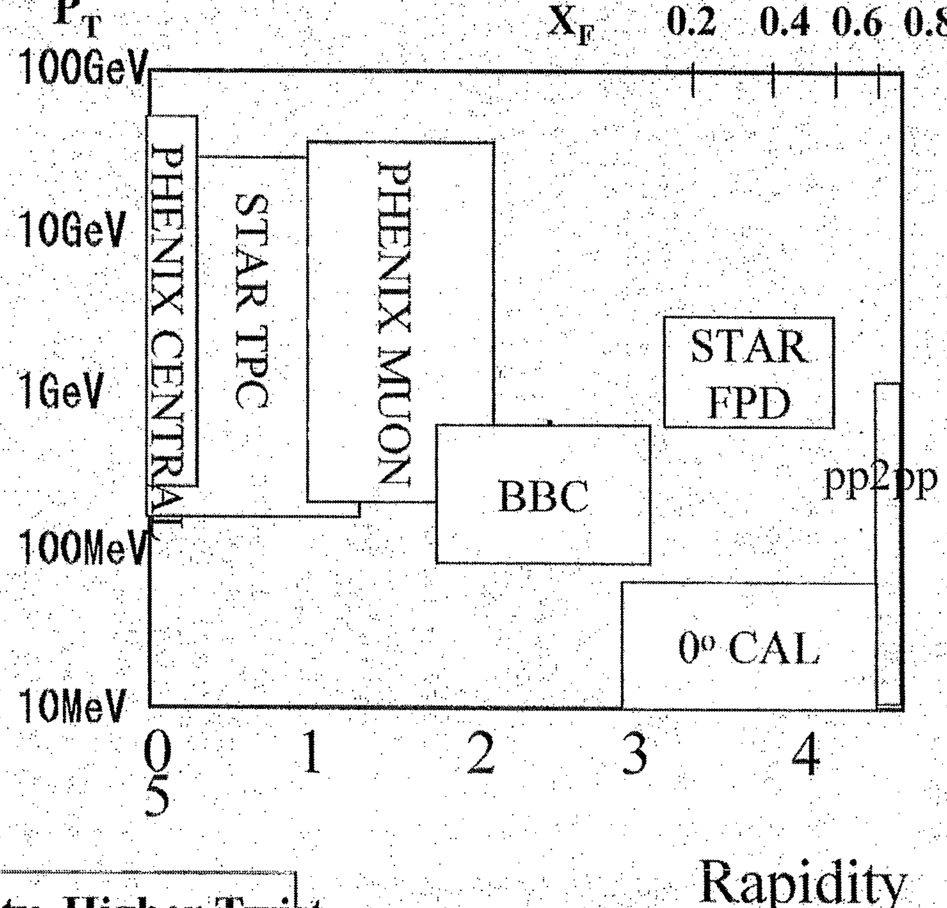
- CEM Parameters are fixed by fitting low energy data
- The result agrees with the CEM prediction at $\sqrt{s}$=200GeV

Physics in A_N (L-R Asymmetry)

useful for local polarimeter for collision point

E704 at Fermilab
at $\sqrt{s}$=20 GeV, p_T=0.5-2.0 GeV/c:

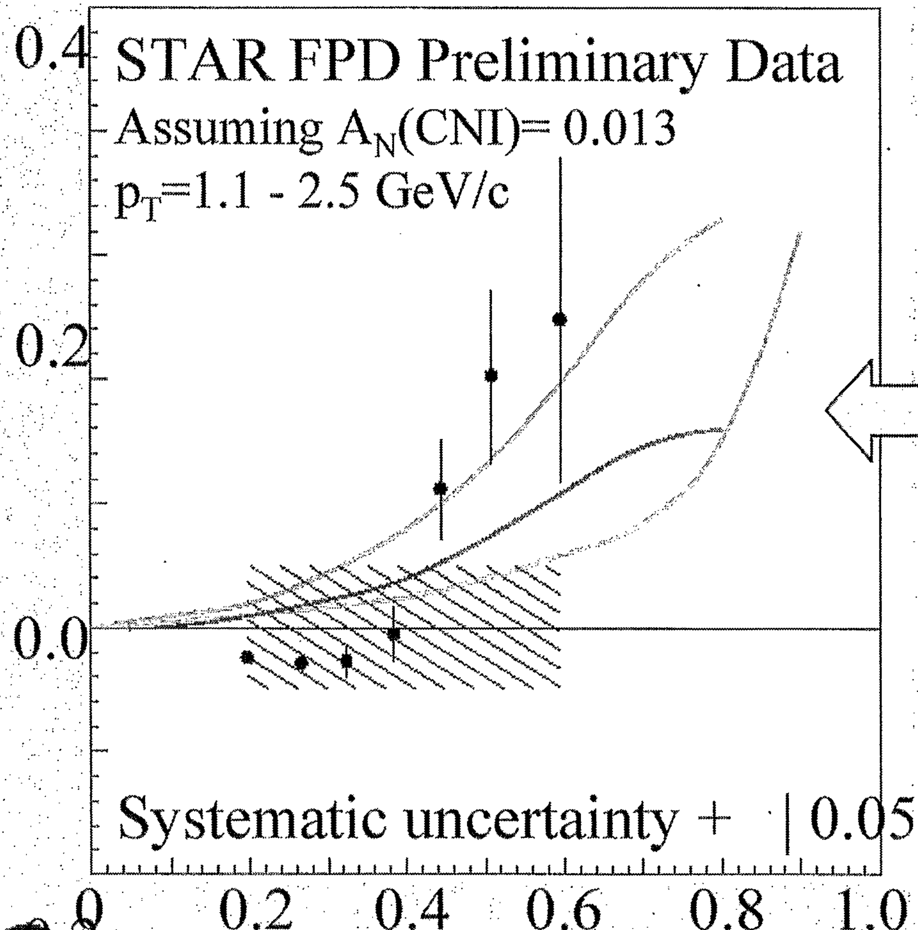




Models:: Transversity, Higher Twist, Fragmentation, kT, Orbital. Etc.

STAR Forward rapidity high x_F $\pi^0 A_N$

$A_N(\pi^0)$ $p^{\uparrow}p \to \pi^0 X$ at $\sqrt{s} = 200 GeV$



$x_F \sim E / 100$

Theory predictions at $p_T = 1.5$ GeV/c

Collins effect
Anselmino, et al.
PRD 60 (1999) 054027.

Sivers effect
Anselmino, et al.
Phys. Lett. B442 (1998) 470.

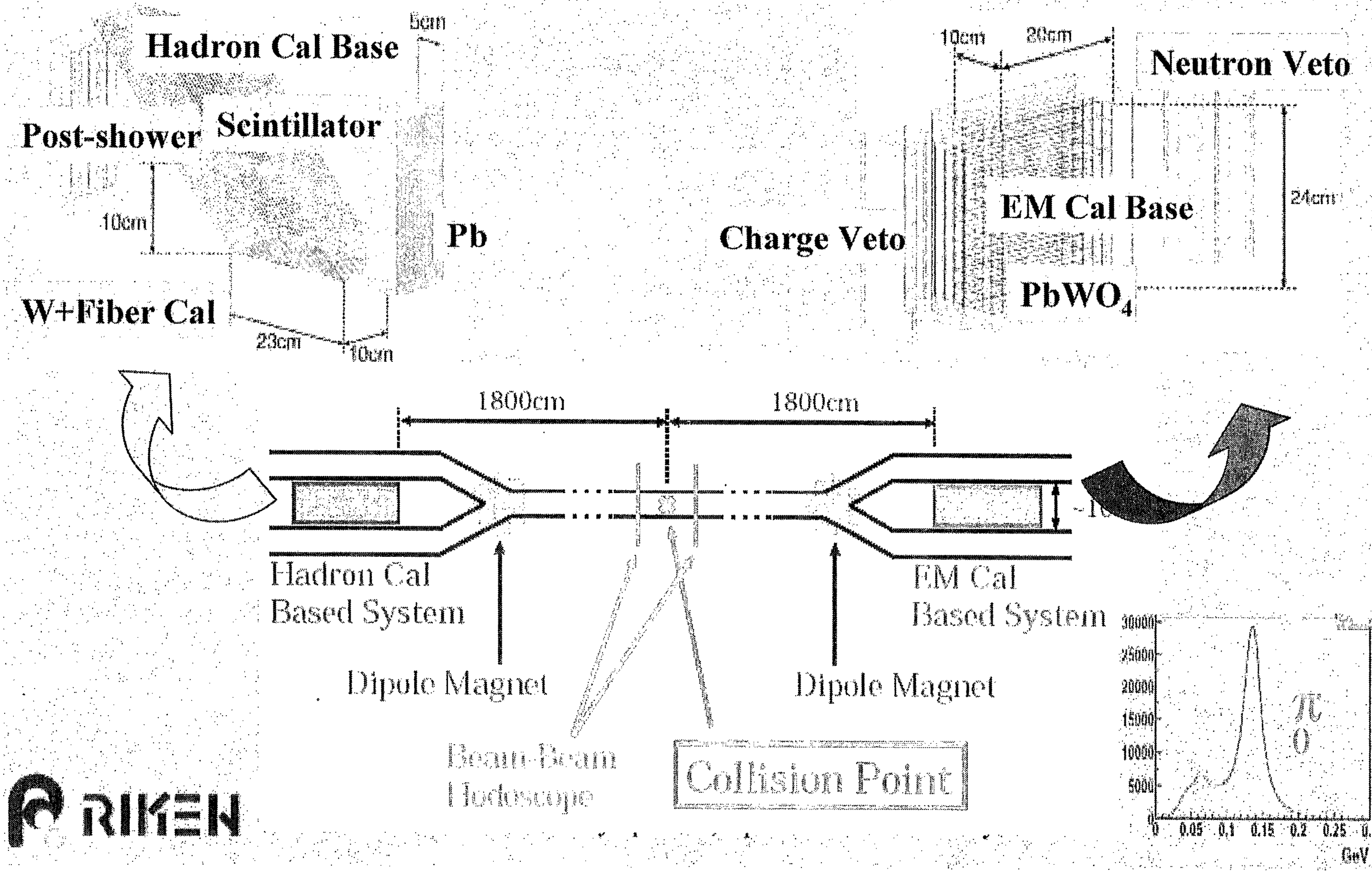
Twist 3 effect
Qiu and Sterman,
Phys. Rev. D59 (1998) 014004.

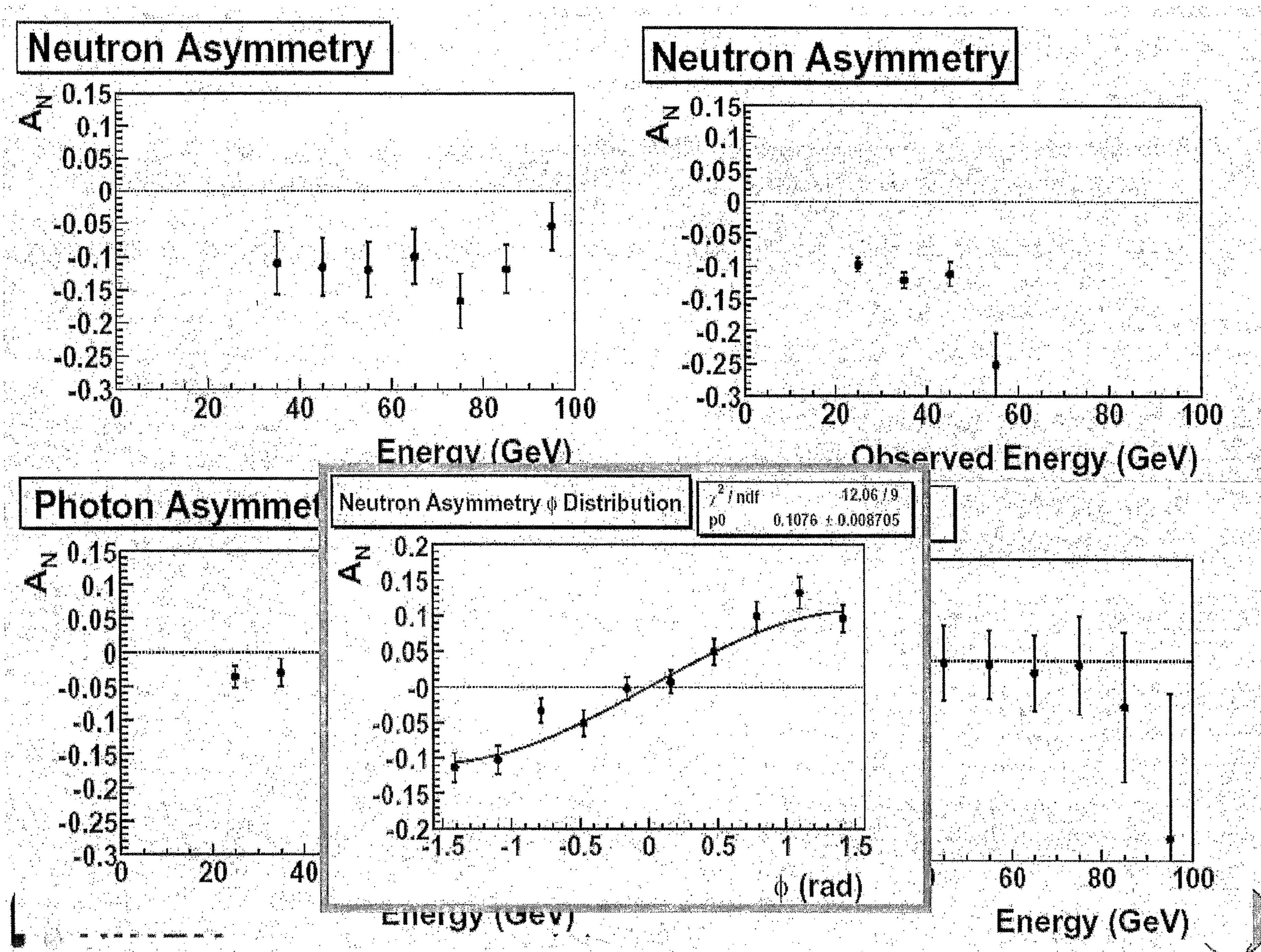
Y.Koike
PaNic02

Spin02 Y.Fukao(Kyoto)
Panic02
M.Togawa(Kyoto)

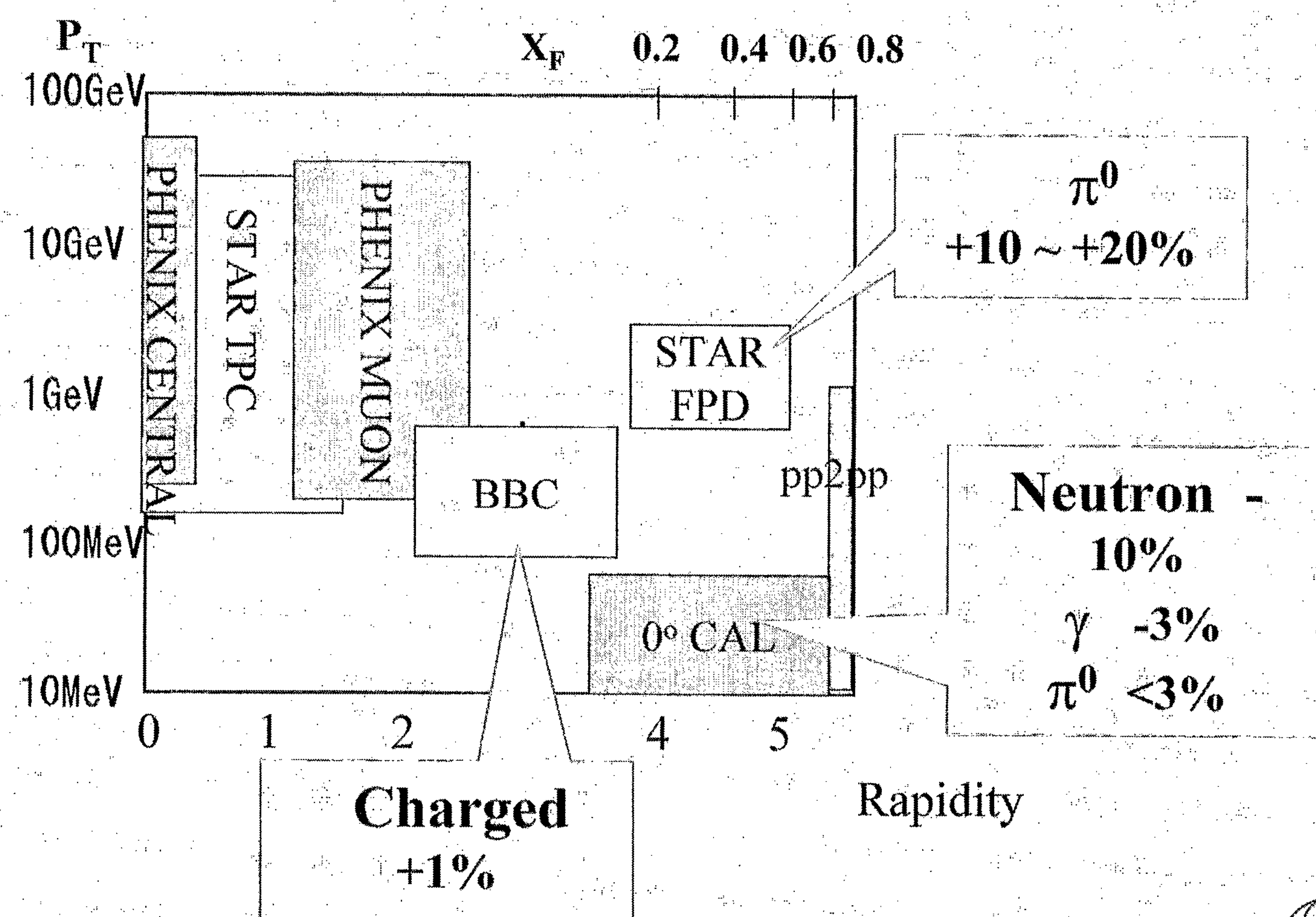
12 O'clock

(local polarimeter for PHENIX)




Neutron Asymmetry
Energy (GeV)
Neutron Asymmetry
Observed Energy (GeV)
Photon Asymmet
Energy (GeV)
Energy (GeV)
Neutron Asymmetry φ Distribution
χ² / ndf 12.06 / 9
p0 0.1076 ± 0.008705
φ (rad)

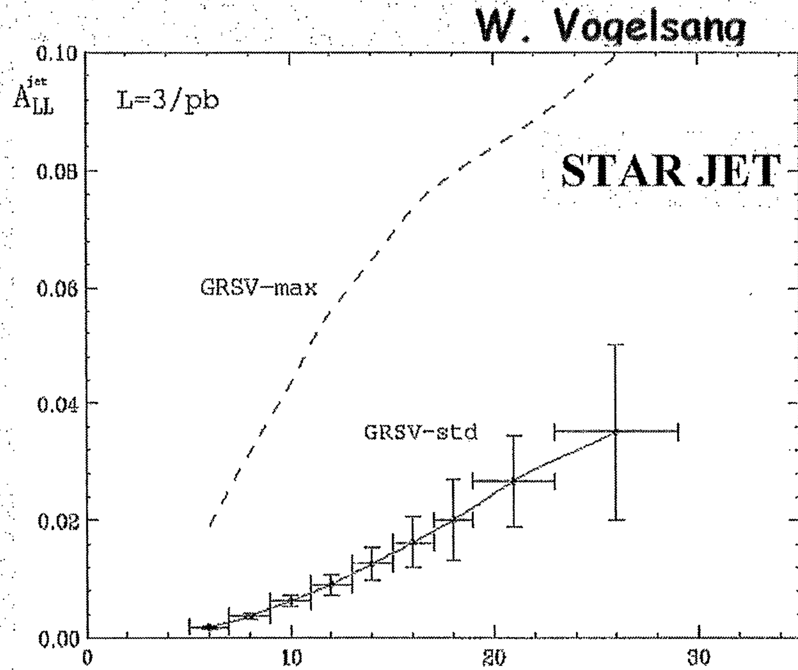
Asymmetries (A_N) seen



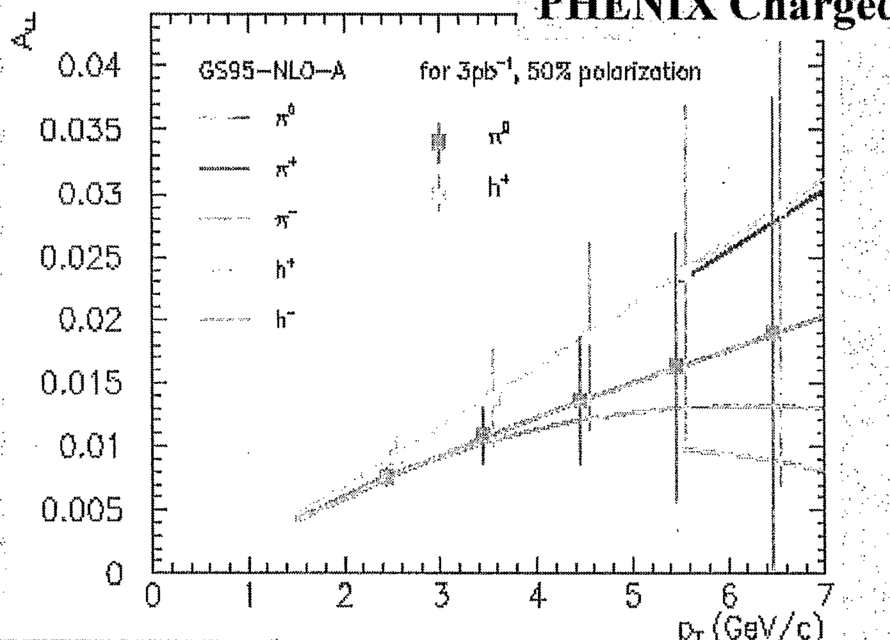
Coming Run with longitudinal polarization $3pb^{-1}$,P=50%

expectations

W. Vogelsang



PHENIX Charged



ΔG will be directly probed

Summary and Outlook

- RHIC spin program has begun. We have a series of program over 5 years to go.
  - Y2001-2, The first polarized proton collision was successfully done with transversely polarized beam, produced unexpected spin phenomena which may relate to unknown behavior of QCD (transversity etc)
  - Y2002-3, The first measurements of helicity asymmetry will SOON be performed @200GeV. Sizable ΔG generates *surprises* in the data.
  - Y2003+, Statistics will be much improved @200GeV, ensuring the *determination of ΔG*. "Spin Crisis" will hopefully be solved by then.
  - Y2005+, Weak Bosons will be produced at RHIC, the NEW "flavor sensitive" tool for the *anti-quark/quark polarization* and unpolarized structure function of anti-quark measurements.
- And beyond...

A DISCUSSION ON THE BEAUTY OF SPIN

Gerry Bunce
RIKEN BNL Research Center
and
Brookhaven National Laboratory

the beauty of

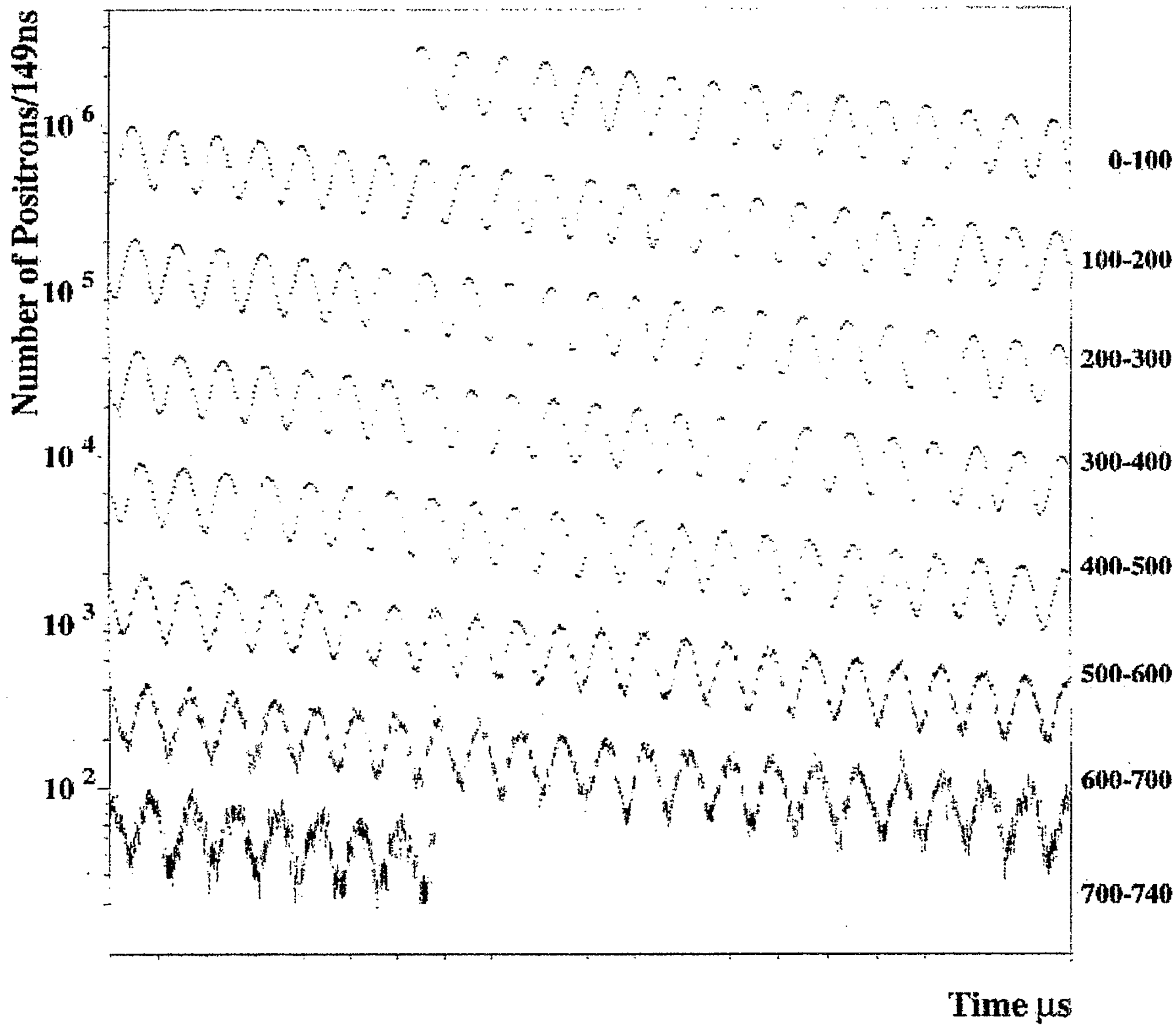
A Discussion on spin

G. Bunce, RBRC

- Why spin?
- $p\Uparrow + p\Uparrow$ and RHIC
- Siberian Snakes
- How do we measure the polarization of the beams?
- First (surprising) results from $\overrightarrow{RHIC}$
- Where are we going?

CCAST Symposium
Beijing
7 April 2003

Muon g-2 Spin Precession at BNL



A prelude: Why spin?

Physics: a search for the unexpected, non-intuitive in nature

- Intrinsic spin
  - point-like particles with quanta of angular momentum!
- proton spin
  $$\vec{p} = \underbrace{\vec{q} + \vec{\bar{q}}}_{\sim 1/4 \text{ of proton spin!}} + \vec{g} + L_{\text{orbital}}$$

Elegance: spin $\Rightarrow$ access to mirror symmetry of physics

Powerful: deeper tests of theoretical understanding with spin

Unexpected order: large spin effects $\Rightarrow$ coherence and order $\Rightarrow$ underlying simplicity

Beauty: spin signals are direct quantum phenomena $\Rightarrow$ amplitudes (not probabilities) $\Rightarrow$ seem to defy intuition

A touch more philosophy...

Spin is often seen as an added complication (and as too complicated!)

- historically: expectations from spin-averaged data are <u>never</u> correct!

Spin experiments have a strong coupling between the accelerator and the experiment

- this is very attractive to many of us
  - many elegant solutions for accelerating polarized particles
- spin experimenters are usually involved in both their experiment and accelerator issues
  - it is fun!

1. p structure → $\vec{\vec{p}}$ structure

A brief history of proton structure

(1) Quark model of proton

u quark: charge $+2/3$
d $-1/3$

SLAC (~1966): quarks real!
color force (3 color charges)

(2) Gluons:
QCD

half of proton momentum is carried by gluons, anti-quarks

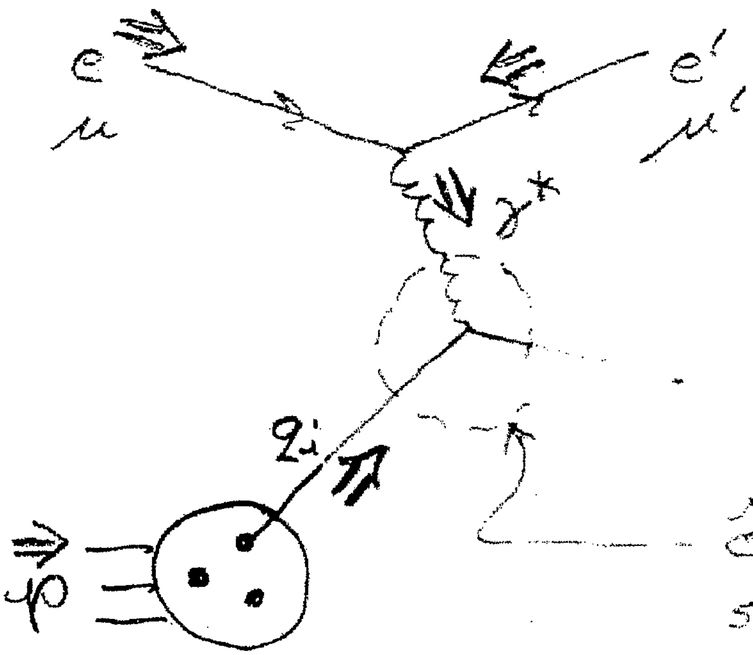
---

(3) Quark model for spin of proton

p spin $\frac{1}{2}$, from valence quarks

(4) $\vec{\vec{e}} + \vec{\vec{p}}$ at SLAC, CERN:
$(q+\bar{q})$ carry 20% ± 5% of p spin

Polarized deep inelastic scattering



$\hat{\sigma}$ angular momentum selection rules:

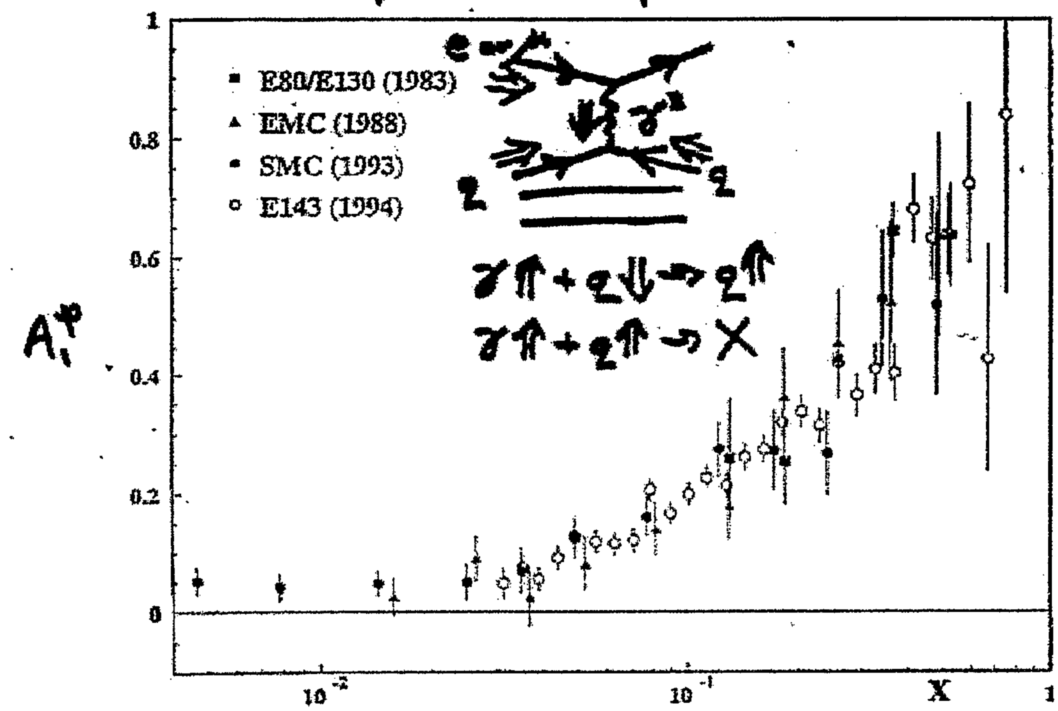
$$\underbrace{\vec{\gamma} + \vec{q}_i}_{\text{spin } 3/2} \to X$$

$$\underbrace{\vec{\gamma} + \overleftarrow{q}_i}_{\text{spin } +1/2} \to \underbrace{\vec{q}_i}_{+1/2}$$

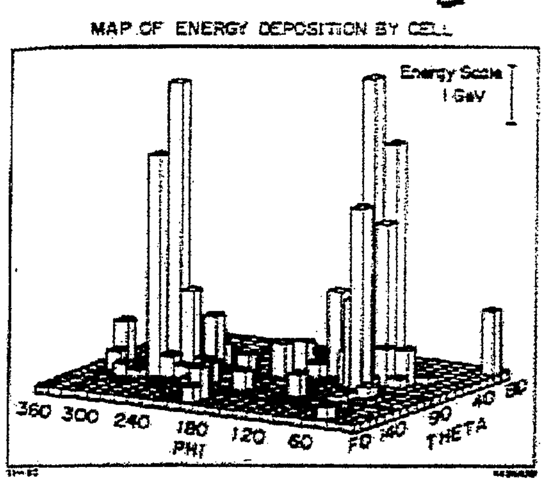
The electron helicity selects the <u>opposite</u> helicity quarks in proton.

→ tool to probe proton spin structure!

At large X, quarks do carry proton spin.



At high p_T, proton beam is a beam of quarks and gluons.



UA2, Paris Conf. 1982

At high p_T, polarized proton beam is a beam of polarized quarks.

The power of RHIC

Proton spin sum rule:

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta q + \Delta \bar{q})}_{\sim 1/4} + \Delta g + L_{orbital}$$

SLAC ($\vec{e} + \vec{p}$), CERN ($\vec{\mu} + \vec{p}$):

- probe proton only via electric charge
- do not distinguish $\vec{q}$, $\vec{\bar{q}}$
- Δgluon is <u>unknown</u>

RHIC: polarized quarks in one $\vec{p}$ probe polarization of gluons in other $\vec{p}$

$$\vec{p} \longrightarrow \quad \longleftarrow \vec{p}$$

- direct measurement of Δgluon
- direct measurement of $\vec{q}$, $\vec{\bar{q}}$ by flavor

Discussion 2: $p^{\Uparrow} + p^{\Uparrow}$ and RHIC

A very short history of $p^{\Uparrow} + p^{\Uparrow}$:

① very difficult to accelerate $p^{\Uparrow}$
due to large g-2 of proton (actually $\frac{g-2}{m_p}$)

② ZGS (Argonne) $p^{\Uparrow}$ to 12 GeV
AGS $p^{\Uparrow}$ to 22 GeV
- fixed target → effective energy $\boxed{\sqrt{s} = 7 \text{ GeV}}$

③ Fermilab $p + A \to \Lambda \to p^{\Uparrow}$ (200 GeV)
- effective energy $\boxed{\sqrt{s} = 20 \text{ GeV}}$
- low intensity

④ RHIC: collide $p^{\Uparrow} + p^{\Uparrow}$
- effective energy $\boxed{\sqrt{s} = 200 - 500 \text{ GeV}}$

→ completely new laboratory to study $p^{\Uparrow}$
→ new domain: many surprises likely

What did these earlier $p\Uparrow$ experiments find?

① at ZGS, $p\Uparrow + p\Uparrow \to p + p$ (90°)

$$\boxed{\frac{\sigma_{\Uparrow\Uparrow}}{\sigma_{\Uparrow\Downarrow}} = 4} \qquad p_T = 2.3 \text{ GeV}/c$$

② at Fermilab, $p + A \to \Lambda\Uparrow + X$

$$\boxed{\frac{N(\Lambda\Uparrow)}{N(\Lambda\Downarrow)} = 2}$$

$p_{protons} = 300$ GeV

$p_T(\Lambda) \gtrsim 1$ GeV/c

(measured to 4 GeV/c)

Also: $\Xi^{\pm}\Uparrow$, $\Sigma^{+,-,0}\Uparrow$, $\Lambda + A \to \Omega^-\Uparrow$

Also: ISR with $\sqrt{s} = 60$.

③ at Fermilab, $p\Uparrow + p \to \pi^{\pm} + X$

$$\boxed{\frac{N(\pi^+ \text{ left}, p\Uparrow)}{N(\pi^+ \text{ left}, p\Downarrow)} = 2.3}$$

$p_{protons} = 200$ GeV

$p_\perp(\pi) \simeq 1.5$ GeV/c

$x_F(\pi) = 0.8$

$R(\pi^-) = .43$

→ <u>spin</u> <u>effects</u> <u>are</u> <u>large</u> <u>at</u> <u>high</u> <u>energy</u>.

pp elastic scattering ~1976

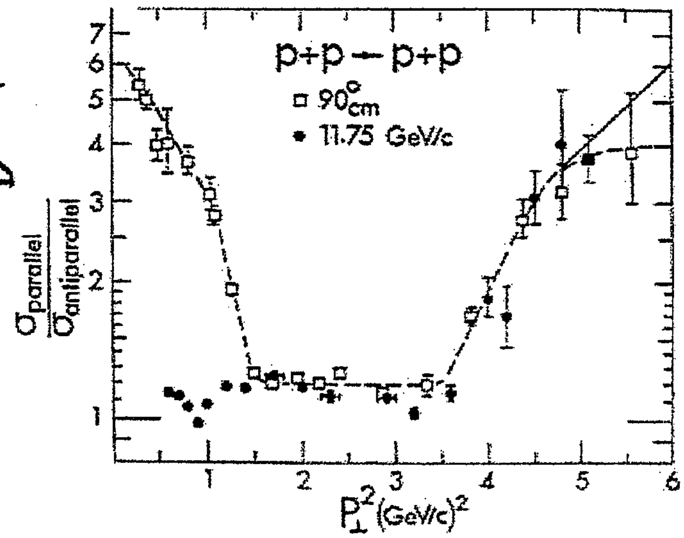


Fig. 3. Ratio of spin-parallel to spin-antiparallel p-p elastic cross-sections plotted against $P_\perp^2$ for fixed energy and fixed angle experiments.

ITERS B

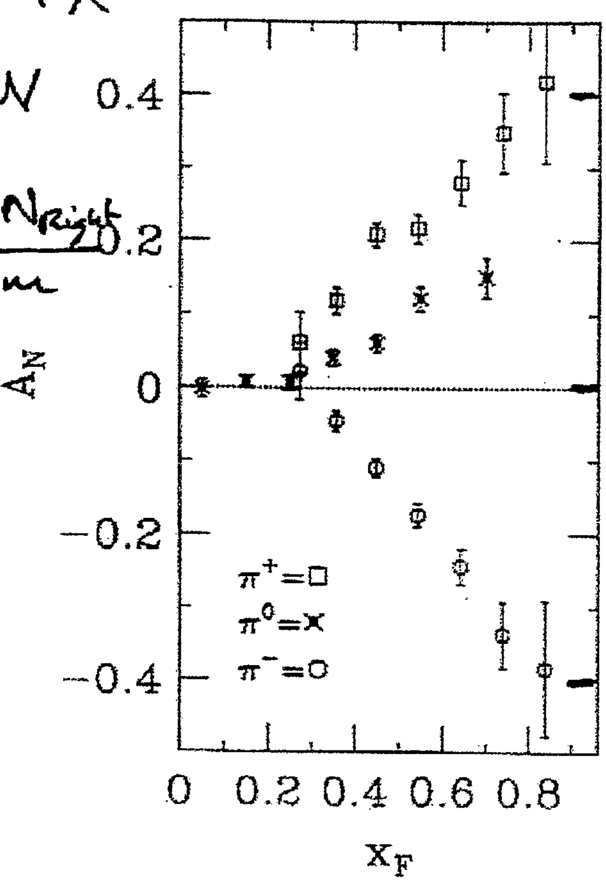
1 August 1991

N_{left}/N_{Right}

$p^{\Uparrow} + p \to \pi + X$

at 200 GeV

$$A_N = \frac{1}{P_{beam}} \frac{N_{left} - N_{Right}}{sum}$$



2.3

1

.43

Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

$p + Be \rightarrow \Lambda + X$
at 300 GeV

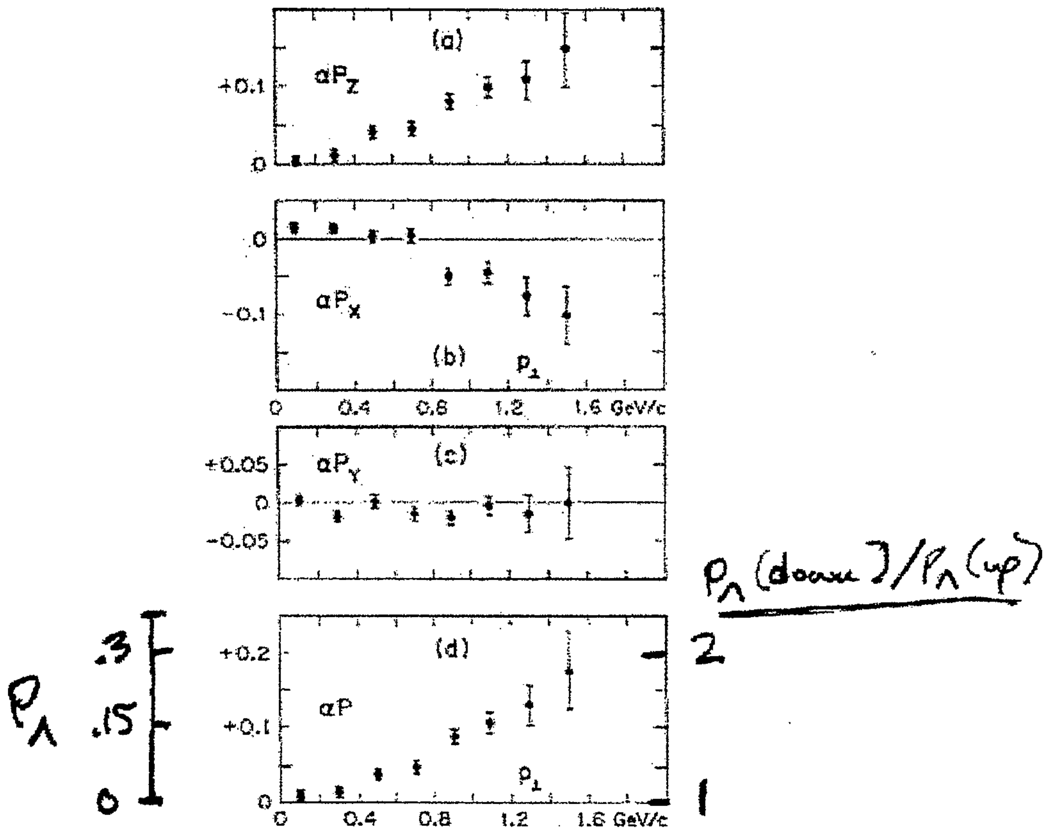
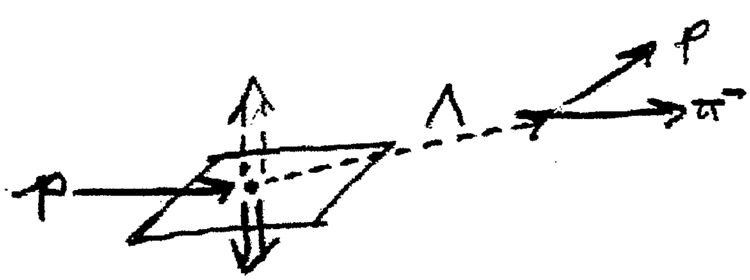


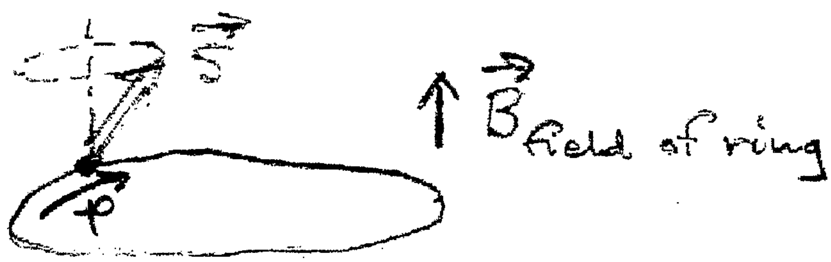
FIG. 3. Three components and magnitude of the $\Lambda^0 \rightarrow p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.



Siberian Snakes

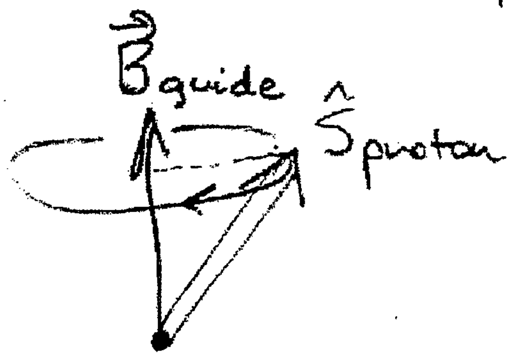
$$\left.\frac{g-2}{2}\right|_{e,\mu} \approx .001 \qquad \left.\frac{g-2}{2}\right|_{\text{proton}} \approx 2$$

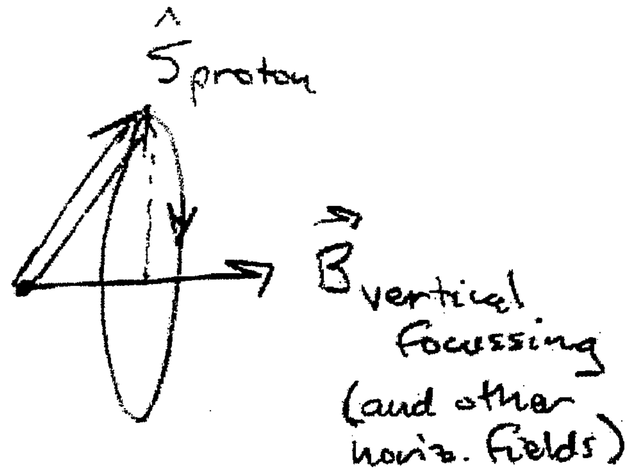
In a circular accelerator/storage ring the spin in the horizontal plane precesses $\boxed{\frac{g-2}{2} \times \gamma}$ full revolutions per turn:



For $\gamma = 100$, $\vec{S}$ precesses $\underline{\underline{200\times}}$ per turn!

What are spin resonances?





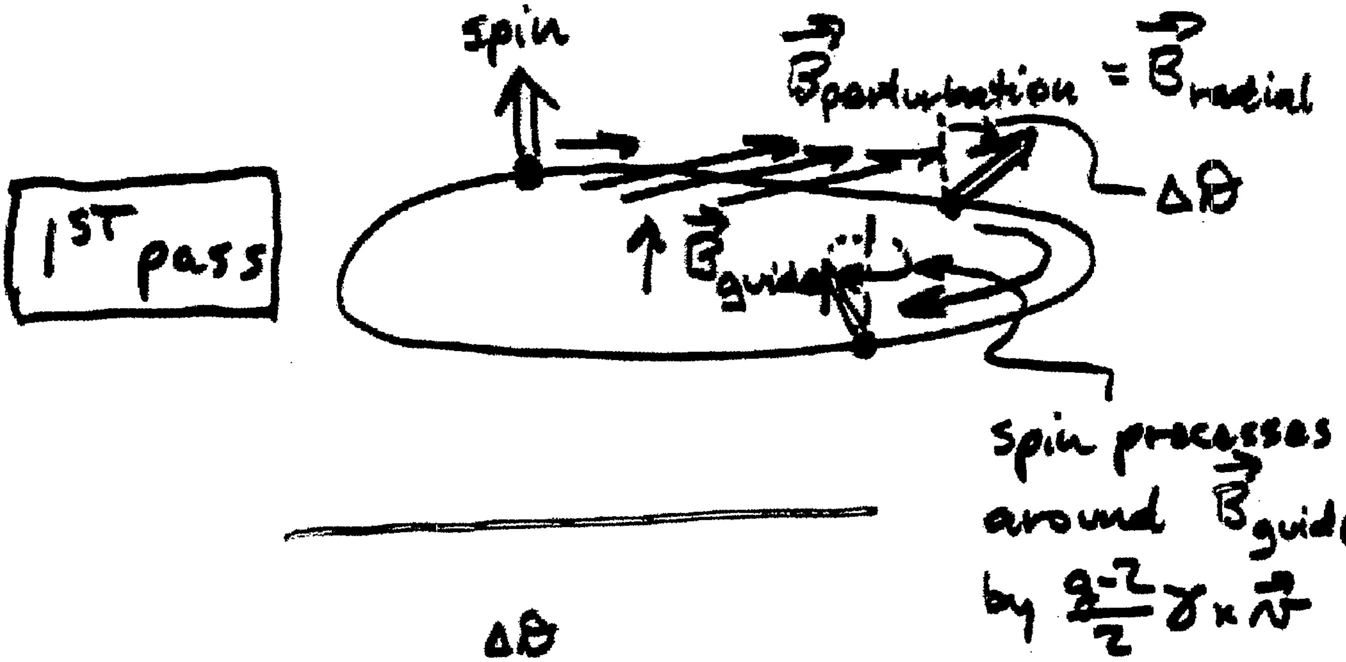
When the two are in phase $\rightarrow$
spin resonance.

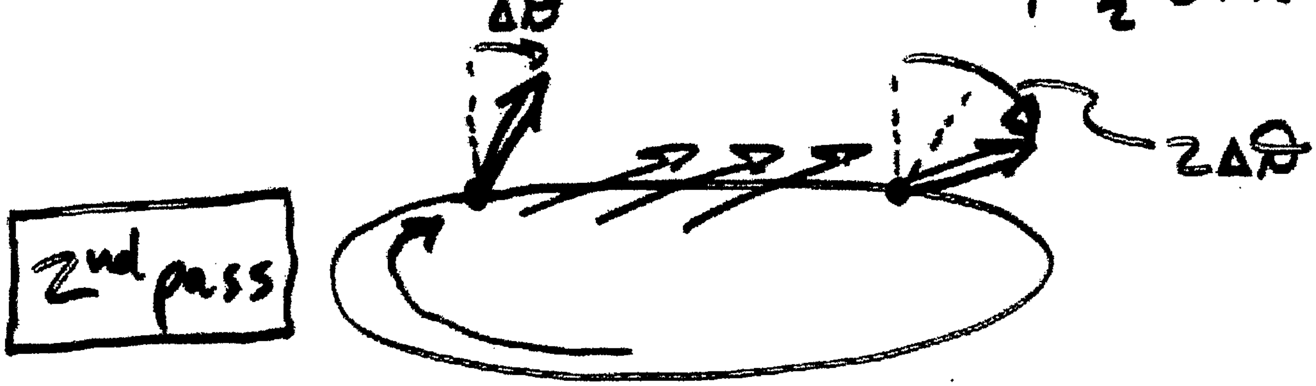
Several solutions:

- jump past energies of spin resonances
  $\rightarrow$ non-adiabatic, blows up beam size

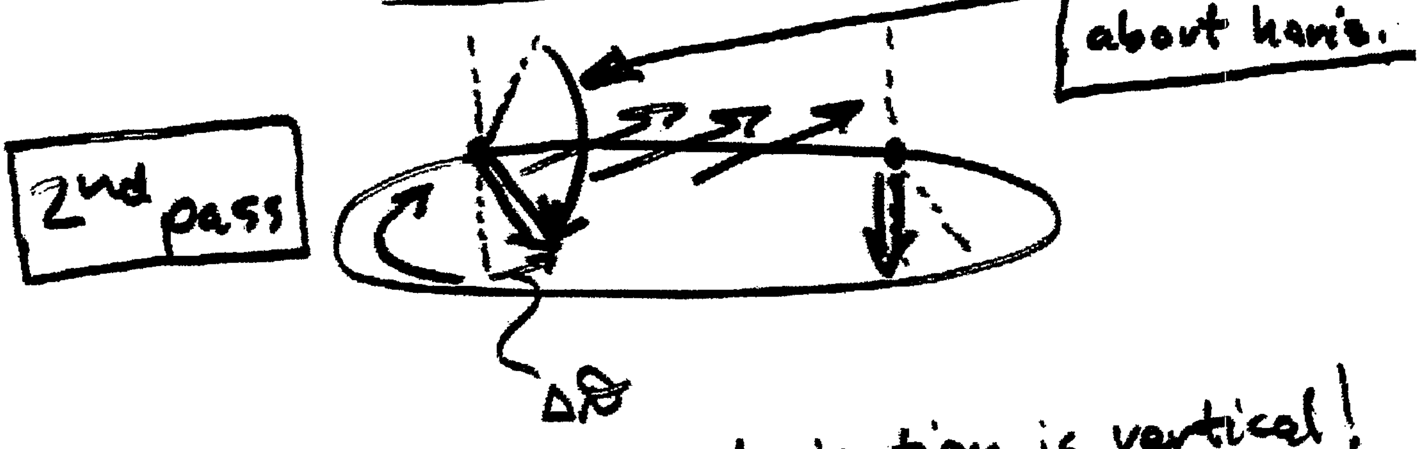
$\rightarrow$ - for a strong resonance, spin flips but polarization is not lost if all the beam sees the resonance

$\rightarrow$ - Siberian Snakes
  - a set of magnets which rotates spin 180° around a horizontal axis





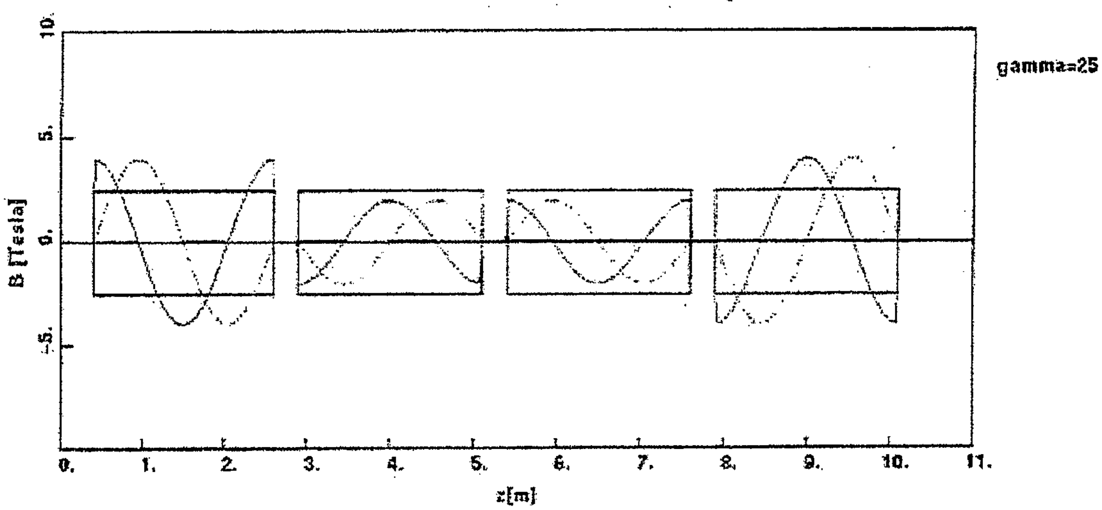
Siberian Snake:

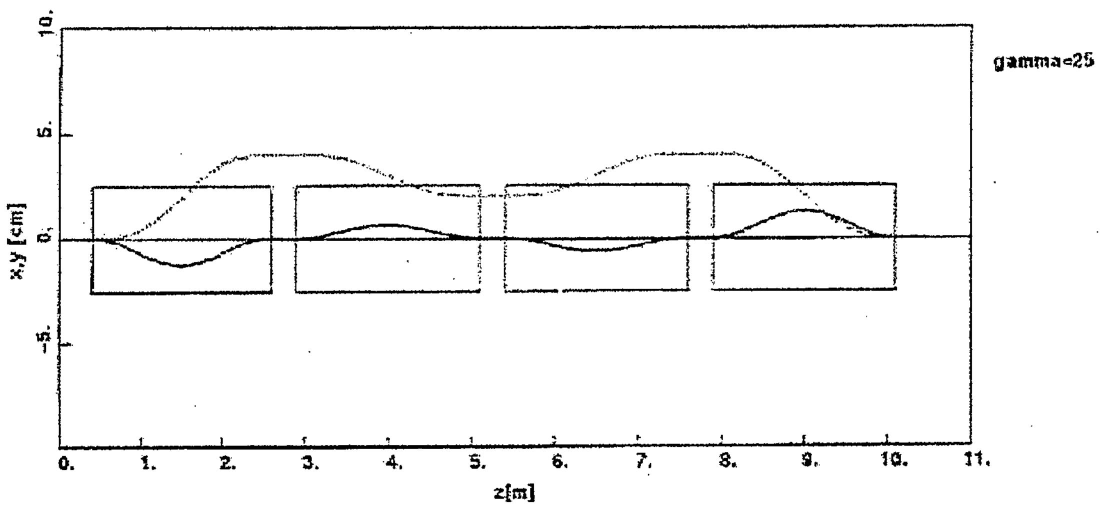


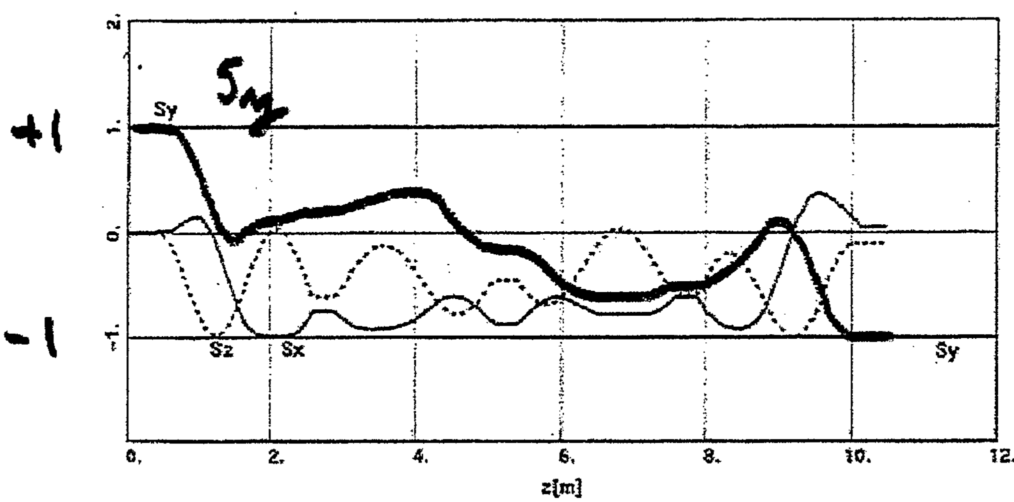
After 2 turns, polarization is vertical!

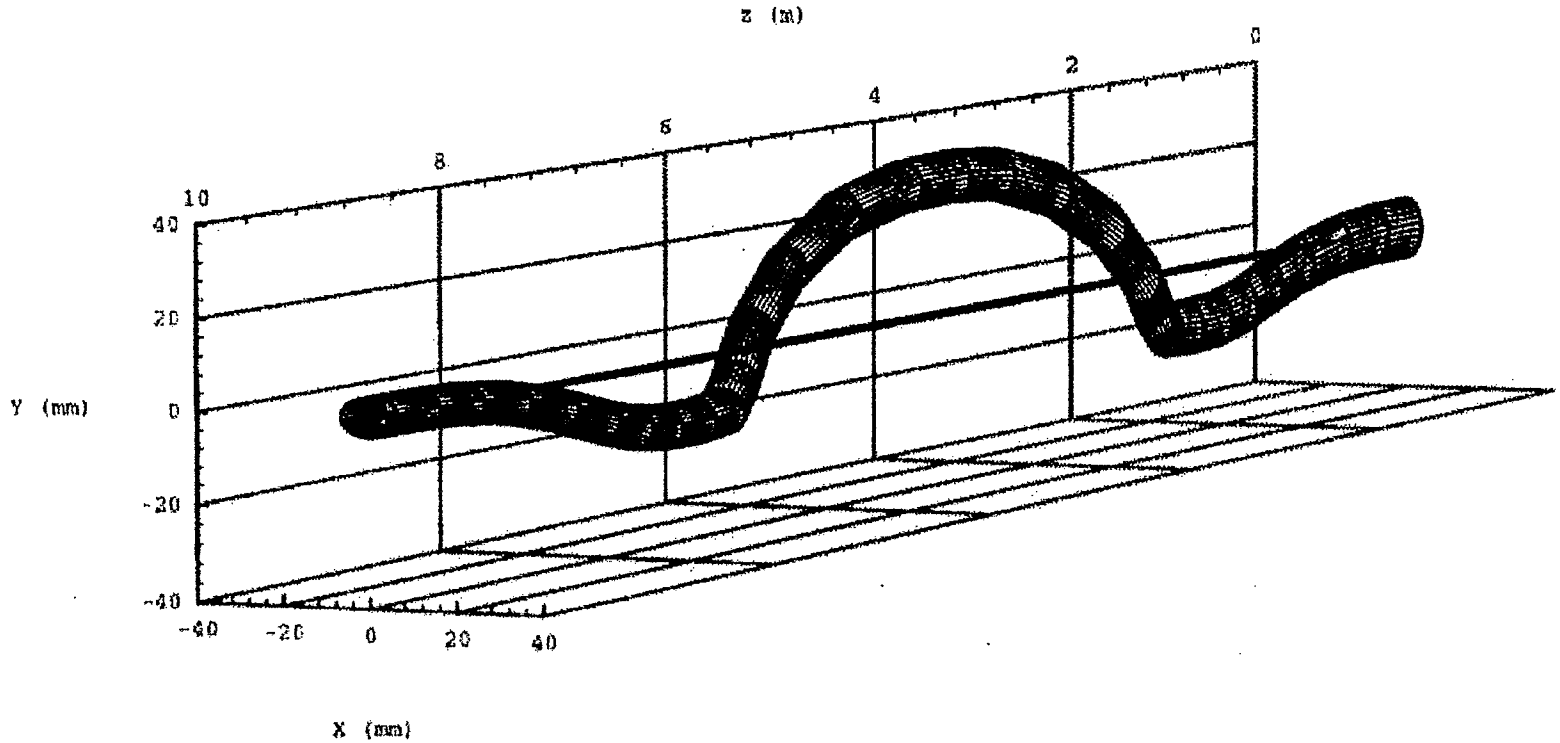
Shatunov, Ptitsin (1997): use 4 helical dipoles → snake.

4-HELIX SNAKE. 1994/01/21.15:50:31 run 4H p.1

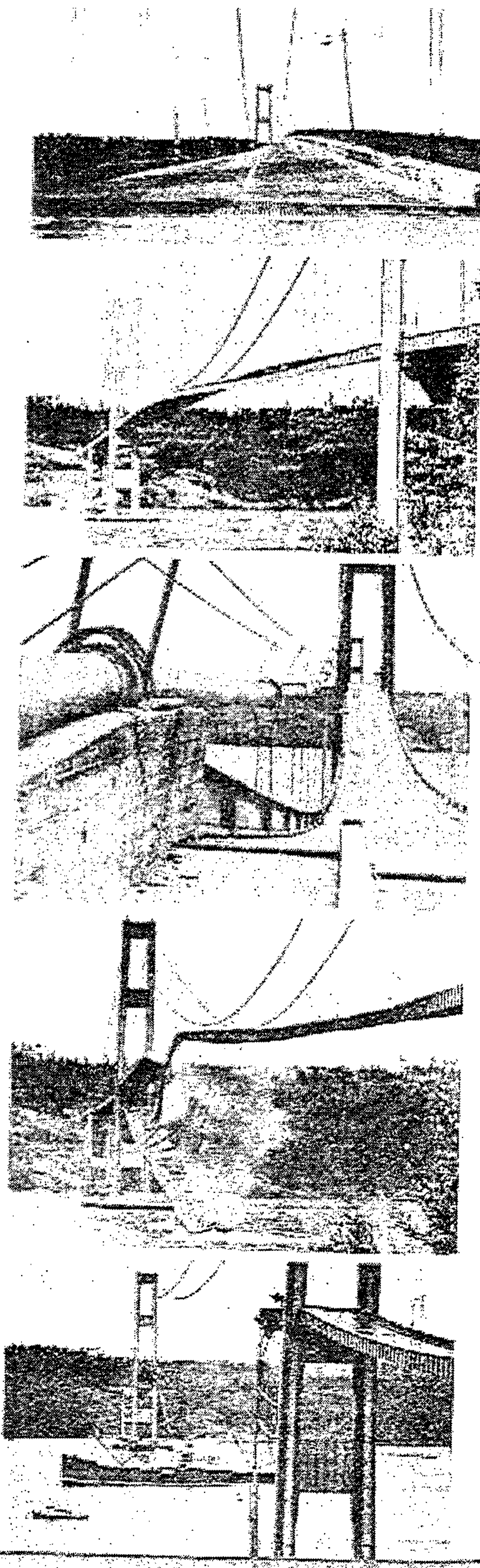


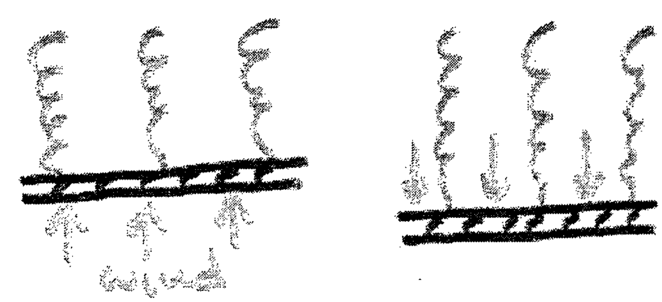





z (m)
0
2
4
6
8
10
40
20
0
-20
-40
Y (mm)
-40
-20
0
20
40
X (mm)

Consider another well-known resonance: the Tacoma Rapids Bridge in 1940:

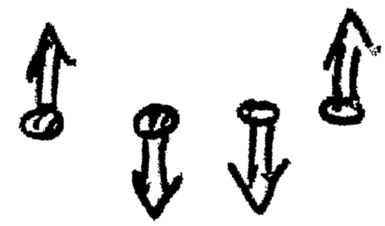




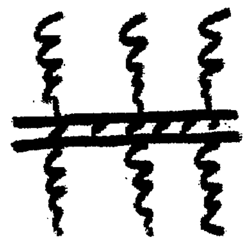
There are many solutions...

Bridge

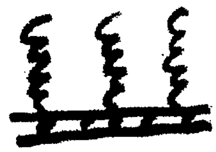
Polarized protons



(1)

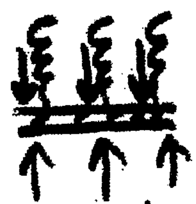


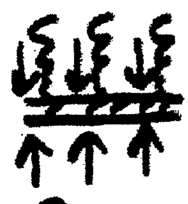
(2)



use particles with different g-2 values

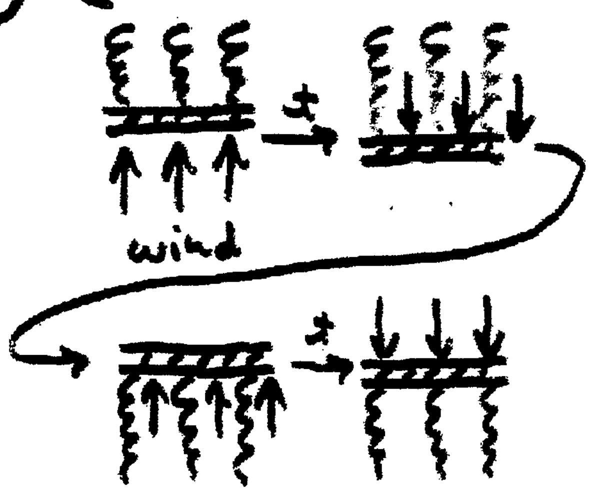
(3)





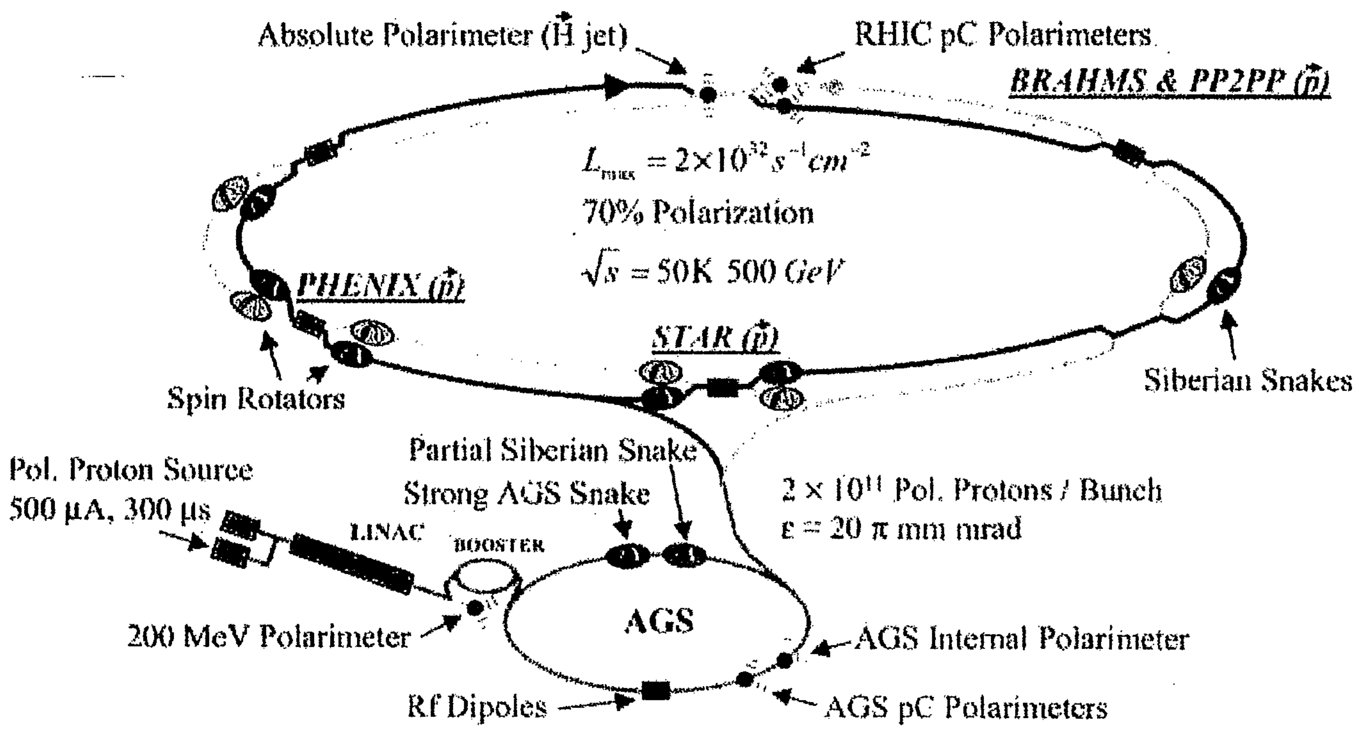
add in correction magnetic field
(AGS: 45 resonances × 96 correction dipoles → 1990)

(4) (the Siberian solution)

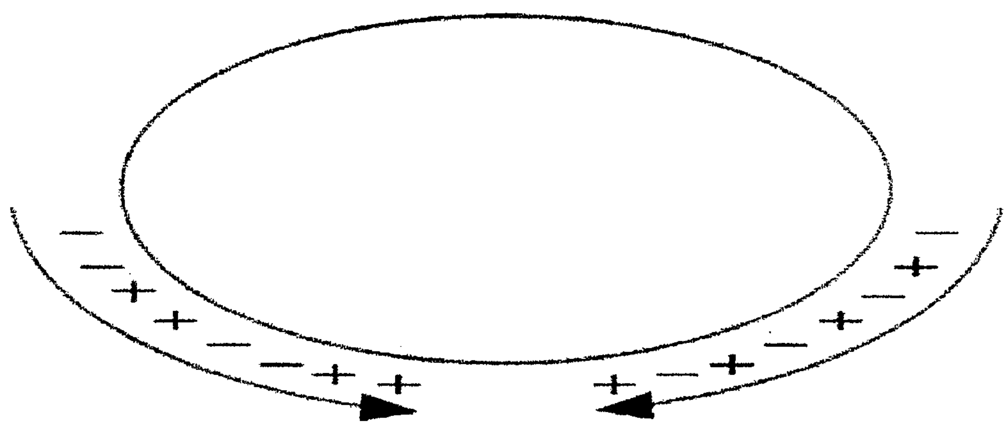


reverse the y component of the spin each pass around the accelerator

Polarized Proton Collisions in RHIC

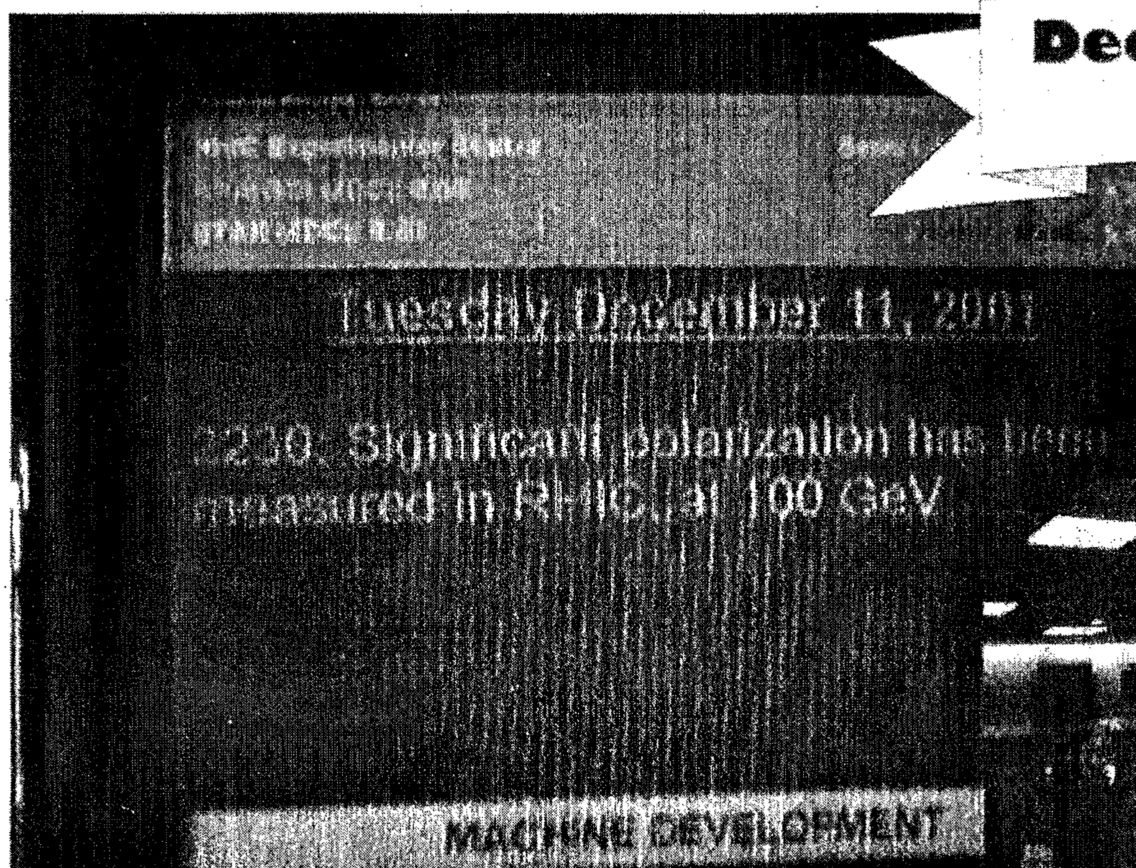


BROOKHAVEN
NATIONAL LABORATORY

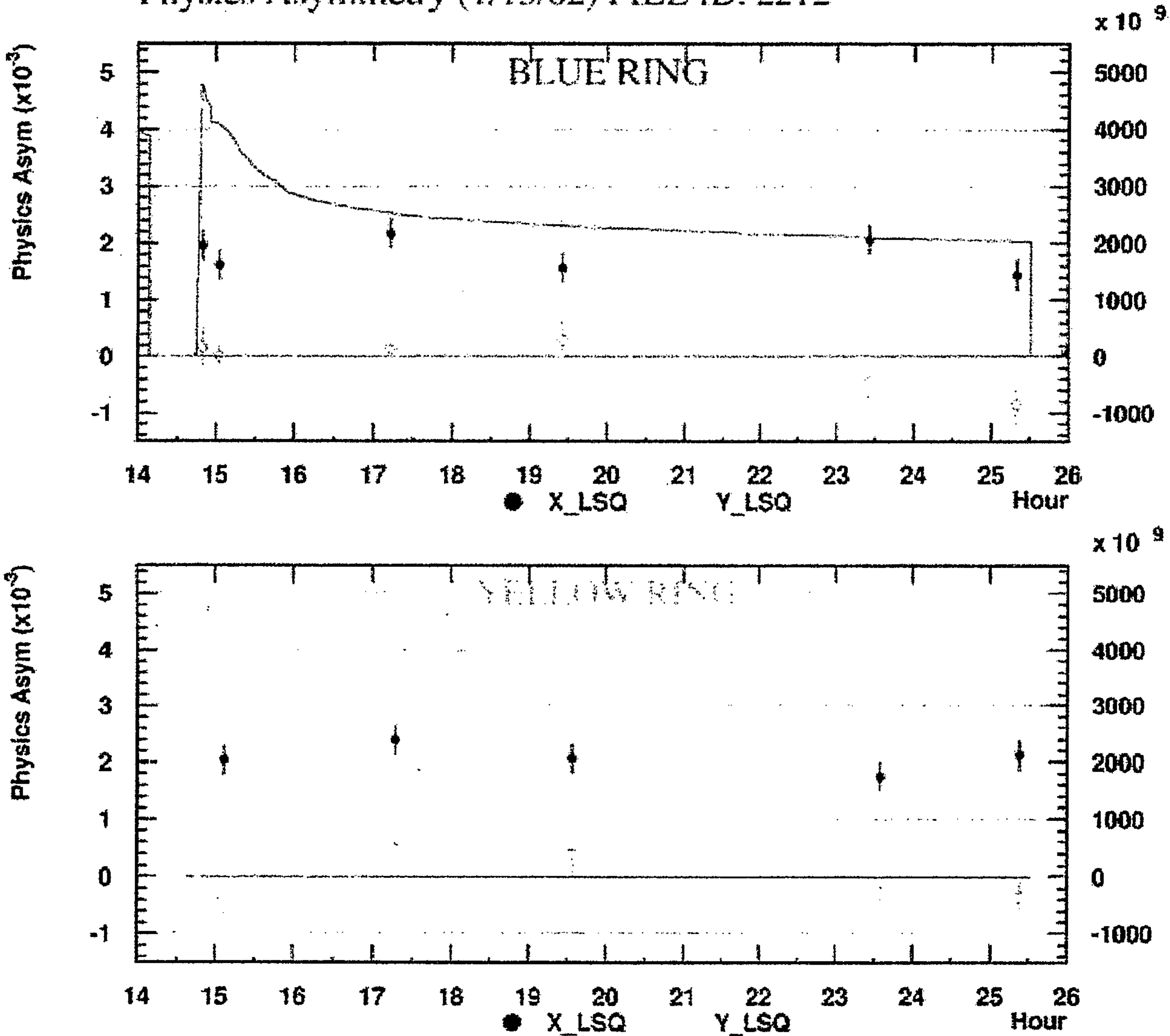


First polarized proton collisions

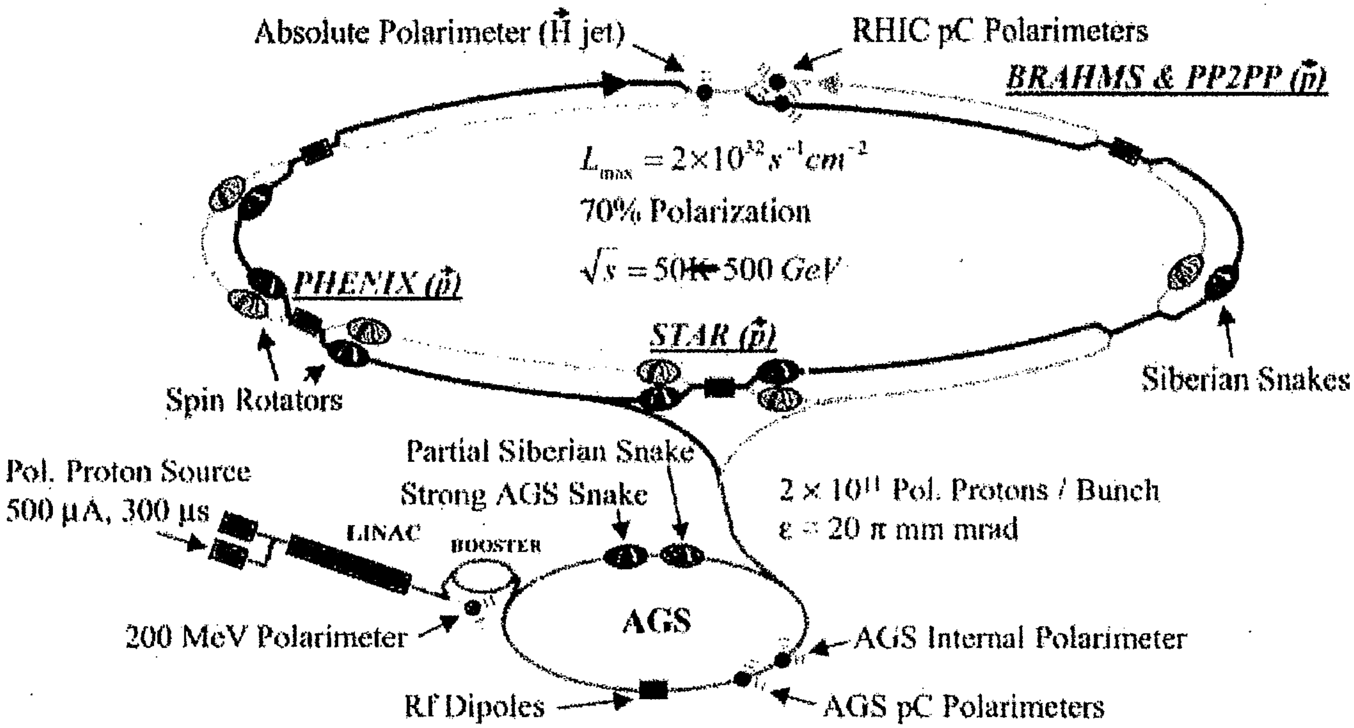
December 11th 2001



Physics Asymmetry (1/13/02) FILL ID: 2212



Polarized Proton Collisions in RHIC



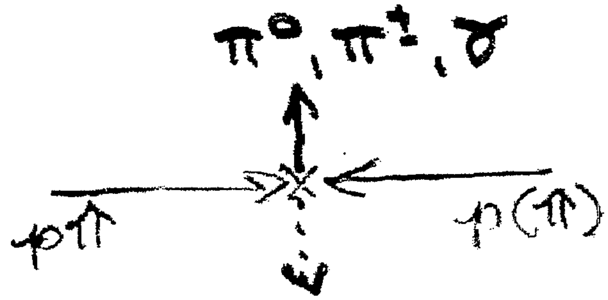
BROOKHAVEN
NATIONAL LABORATORY

The First RHIC Spin Run

$$p\Uparrow + p\Uparrow \to \left.\begin{matrix}\pi^0 \\ \pi^\pm \\ n\end{matrix}\right\} + X$$

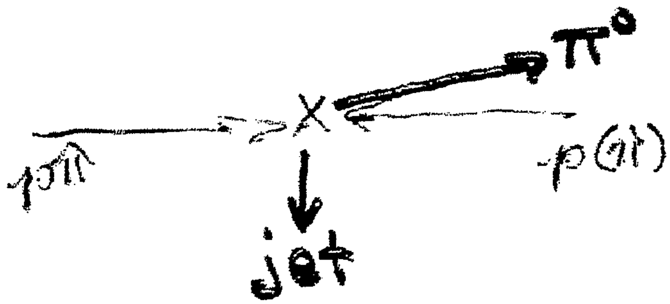
$$\boxed{\sqrt{s} = 200} \qquad p + p$$

(1) mid-rapidity:



PHENIX, STAR

(2) forward:

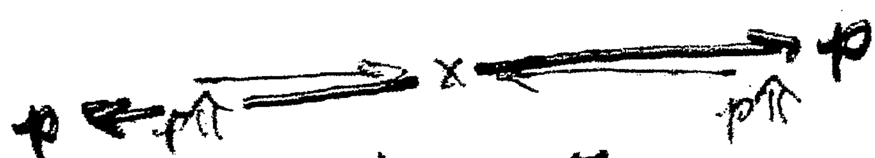


STAR

(3) very forward:

Local Pol.
(12 o'clock)

(4) elastic:



pp2pp

$-t \approx .005$

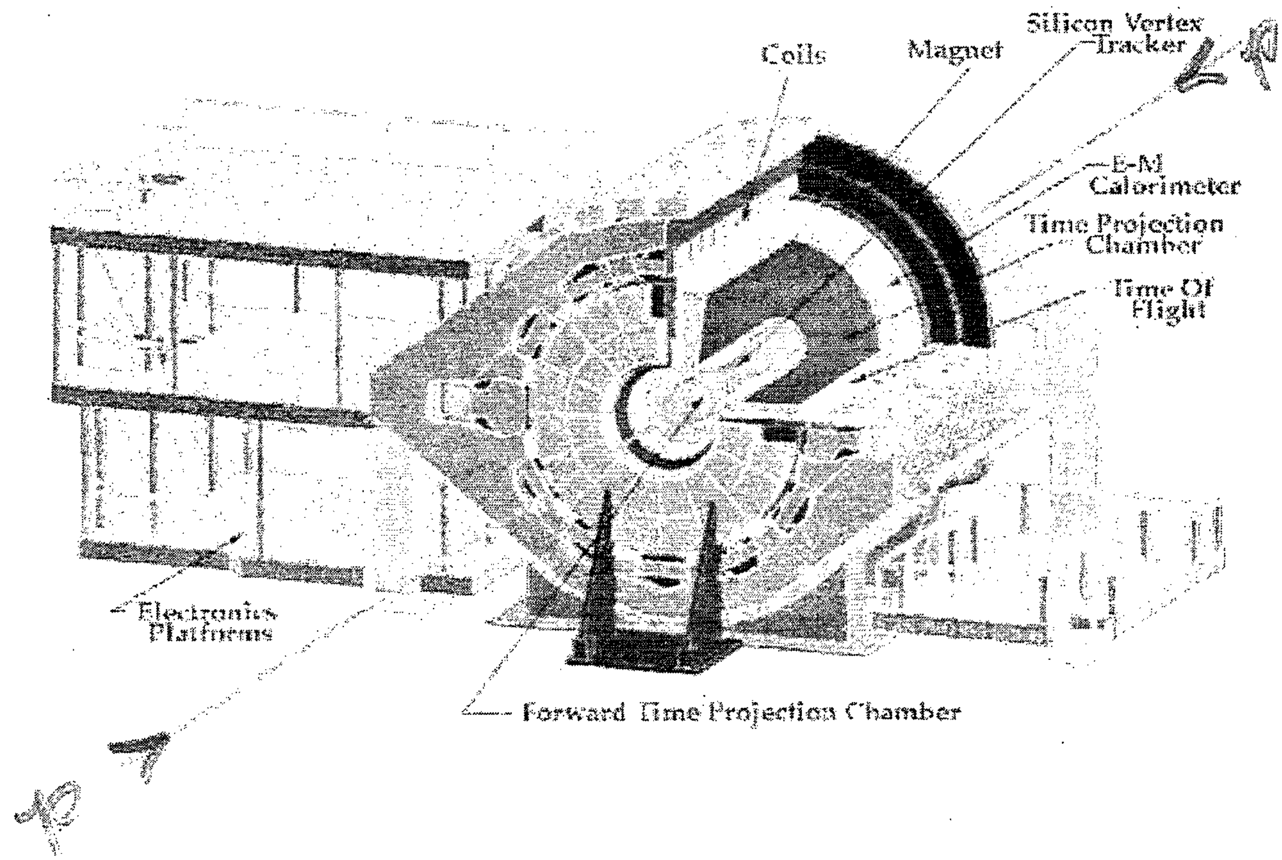
Yellow beam
polarized
(vertical) $\Uparrow$

Blue beam
<u>un</u>polarized

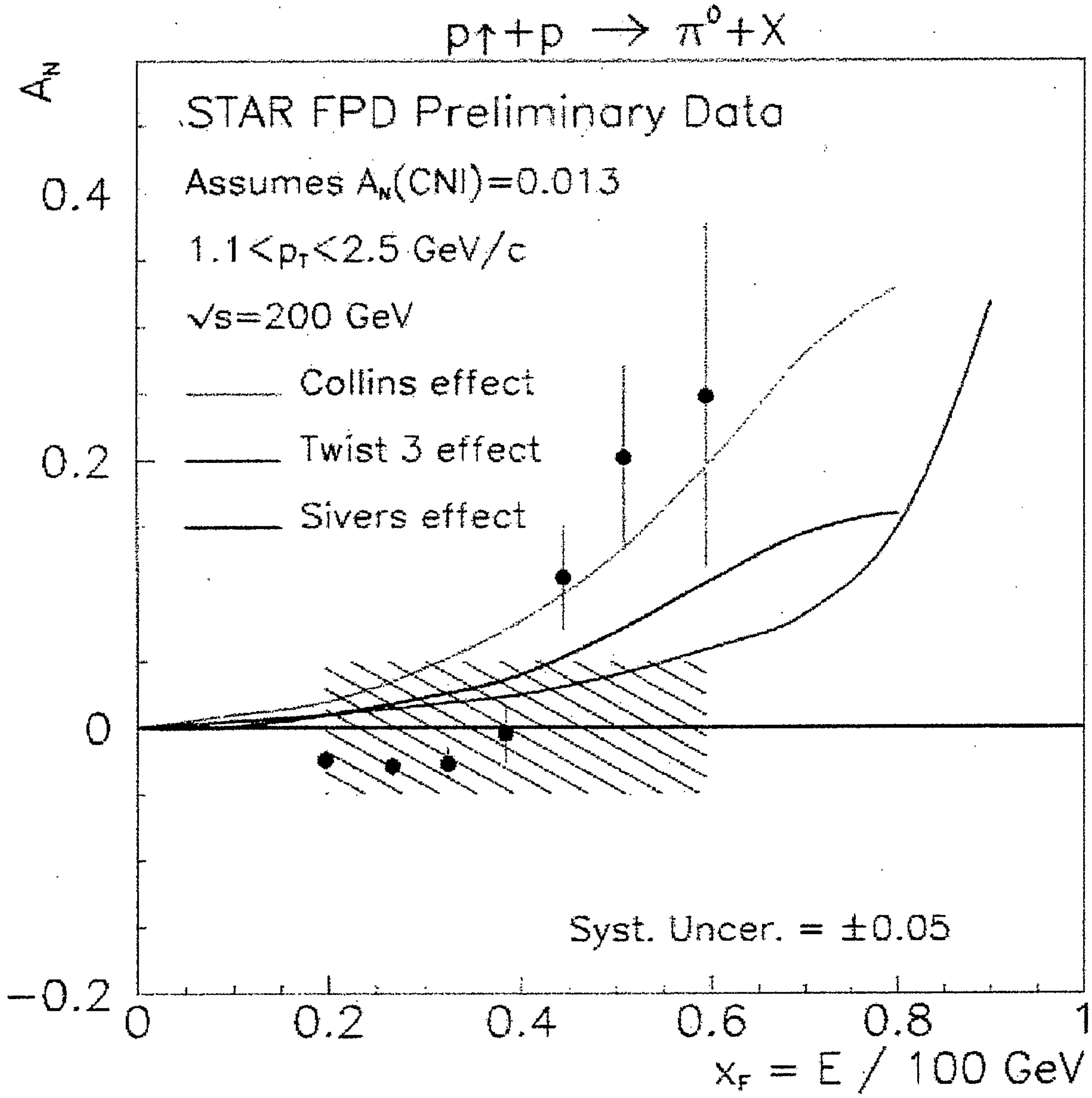
Forward "π^0" detector

$$p\uparrow + p\uparrow \to \pi^0 X$$
$$\hookrightarrow \gamma + \gamma$$

STAR Detector



$$A_N = \frac{1}{P_{Yellow}} \times \frac{N_{\Uparrow}(\pi^0, \text{left})/L_{\Uparrow} - N_{\Downarrow}(\pi^0, \text{left})/L_{\Downarrow}}{\text{''} \quad + \quad \text{''}}$$



Interesting! What is the physics?

neutron asymmetry:

- very forward, $p_T < .5$ GeV/c
  - $\Rightarrow$ definitely soft physics
  - $p\Uparrow + p \to \Delta + X$ (or basically exclusive?)
  - $\hookrightarrow n + \pi$
  - (any small asymmetry is also seen in the beam-beam counters at STAR — π?)

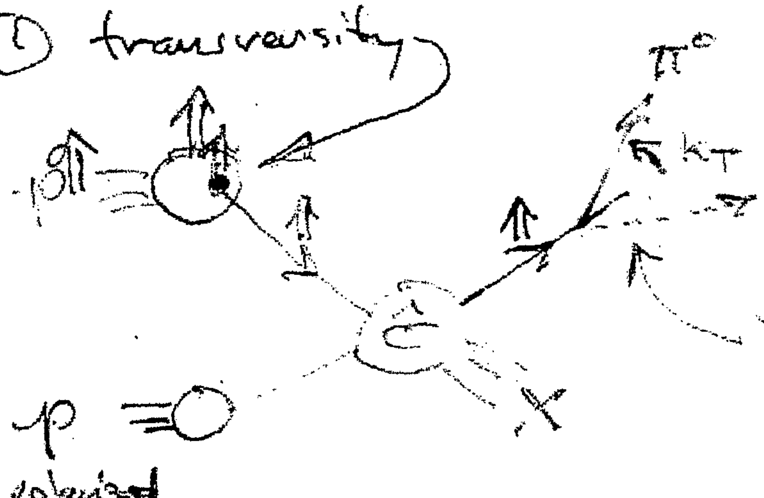
π^0 asymmetry?

- p_T 1.5-3 GeV/c, large x_F
  - just like $\sqrt{s} = 20$ GeV
  - but $$\left.\frac{N_{jets}(\pi^0)}{N(\pi^0)}\right|_{\sqrt{s}=200} \approx 5 \times \left.\frac{N_{jets}(\pi^0)}{N(\pi^0)}\right|_{\sqrt{s}=20}$$
  - just from Pythia
    - real model of hard physics
    - hand-tweaked model of soft physics $\to$ correct σ

π^0 asymmetry (cont.)

Models:

① transversity



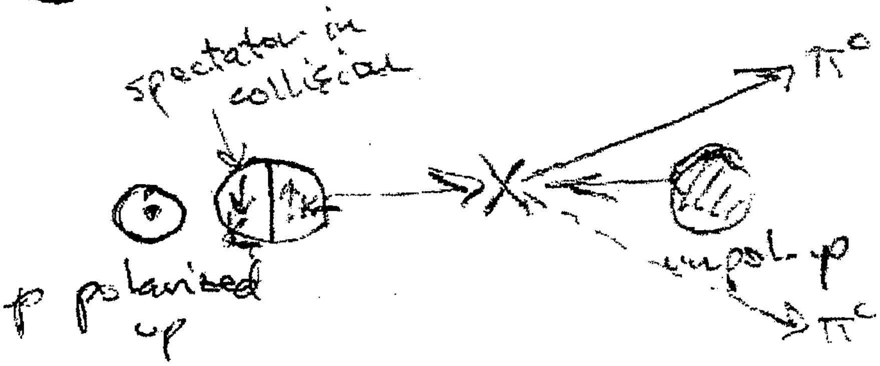
analyzing power of π^0 from polarized quark (Heppelmann-Collins)

– many "buts".

– $e^+e^- \to q^{\Uparrow} \bar{q}^{\Uparrow}$, $\bar{q} \to \pi$, $q \to \pi$ } correlation ← to be done at Belle

(earlier study $A \sim .06$, but kinematics?)

② initial state effect from k_T



$P_T = p_T + k_T$

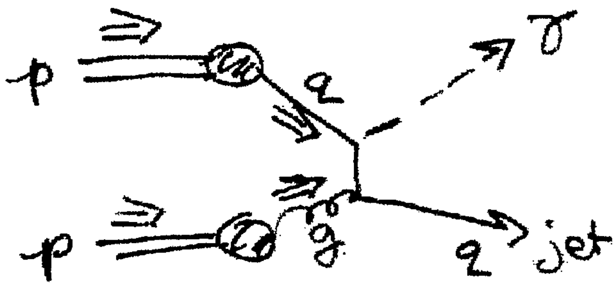
$\boxed{\text{left-right asymmetry}}$

$P_T = p_T - k_T$

RHIC Spin Probes

Gluon polarization:

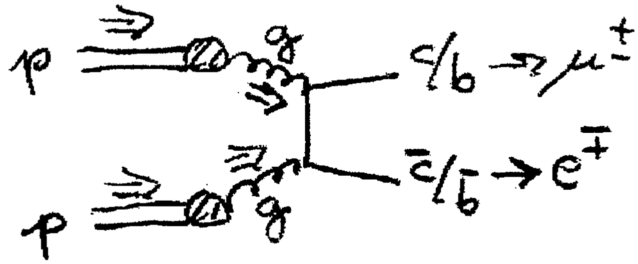
$$A_{LL} = \frac{1}{P^2}\,\frac{N_{++}(\theta) - N_{+-}(\theta)}{N_{++} + N_{+-}}$$



$$A_{LL} = \frac{\Delta G}{G}(x_g)\, A_1^p(x_q)\, \hat{a}_{LL}$$

$$(.3) \quad (.6)$$

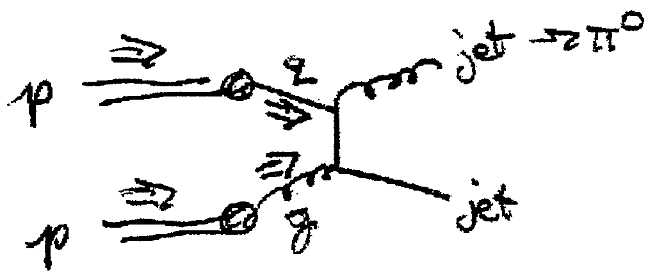
$$\simeq \frac{1}{5}\,\frac{\Delta G}{G}(x_g)$$



$$A_{LL} = \frac{\Delta G}{G}(x_1)\,\frac{\Delta G}{G}(x_2)\,\hat{a}_{LL}$$

$$(.5?) \quad (.15)$$

$$\overset{?}{\simeq} \frac{1}{12}\,\frac{\Delta G}{G}(x_1)$$



$$A_{LL} = \frac{\Delta G}{G}(x_1)\,\frac{\Delta u}{u}(x_2)\,\hat{a}_{LL}$$

$$(.4) \quad (.6)$$

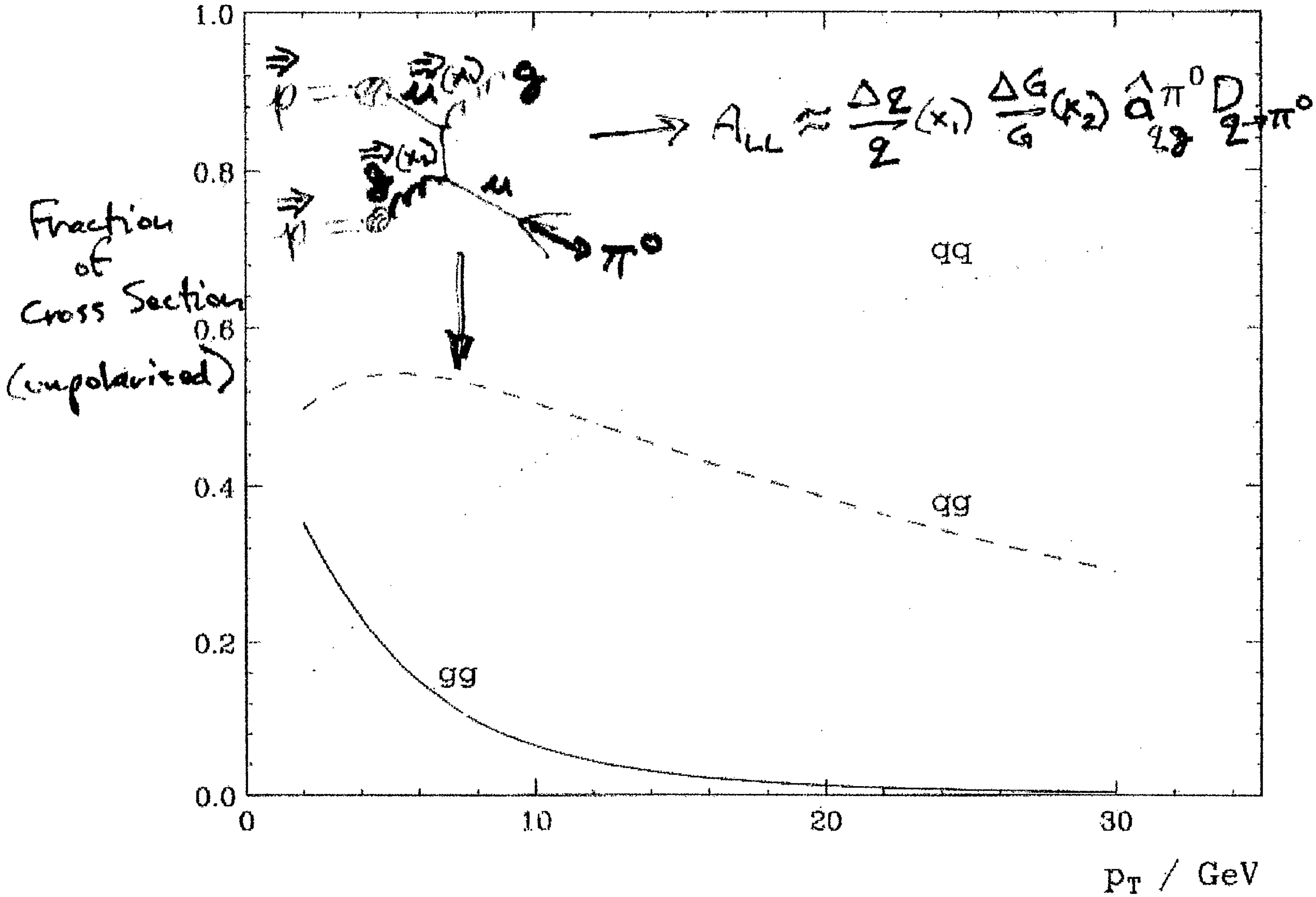
$$\simeq \frac{1}{4}\,\frac{\Delta G}{G}(x_1)$$

$+ gg \to gg/q\bar{q}$

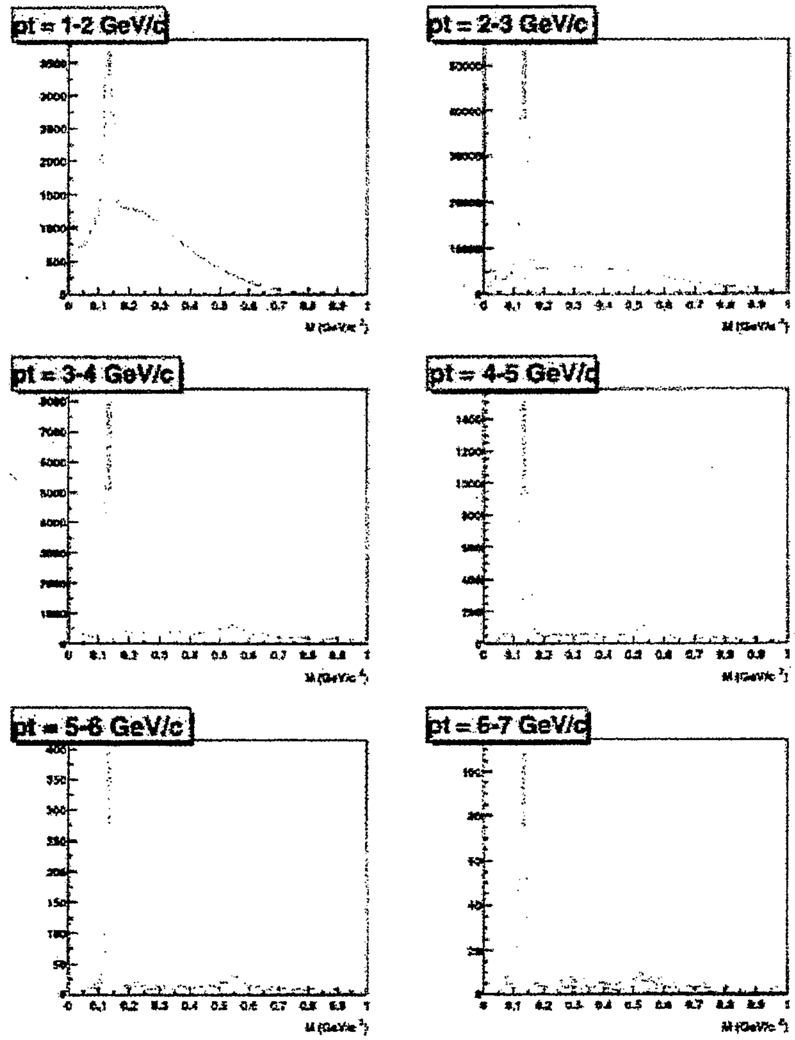
also J/ψ (but production mechanism)

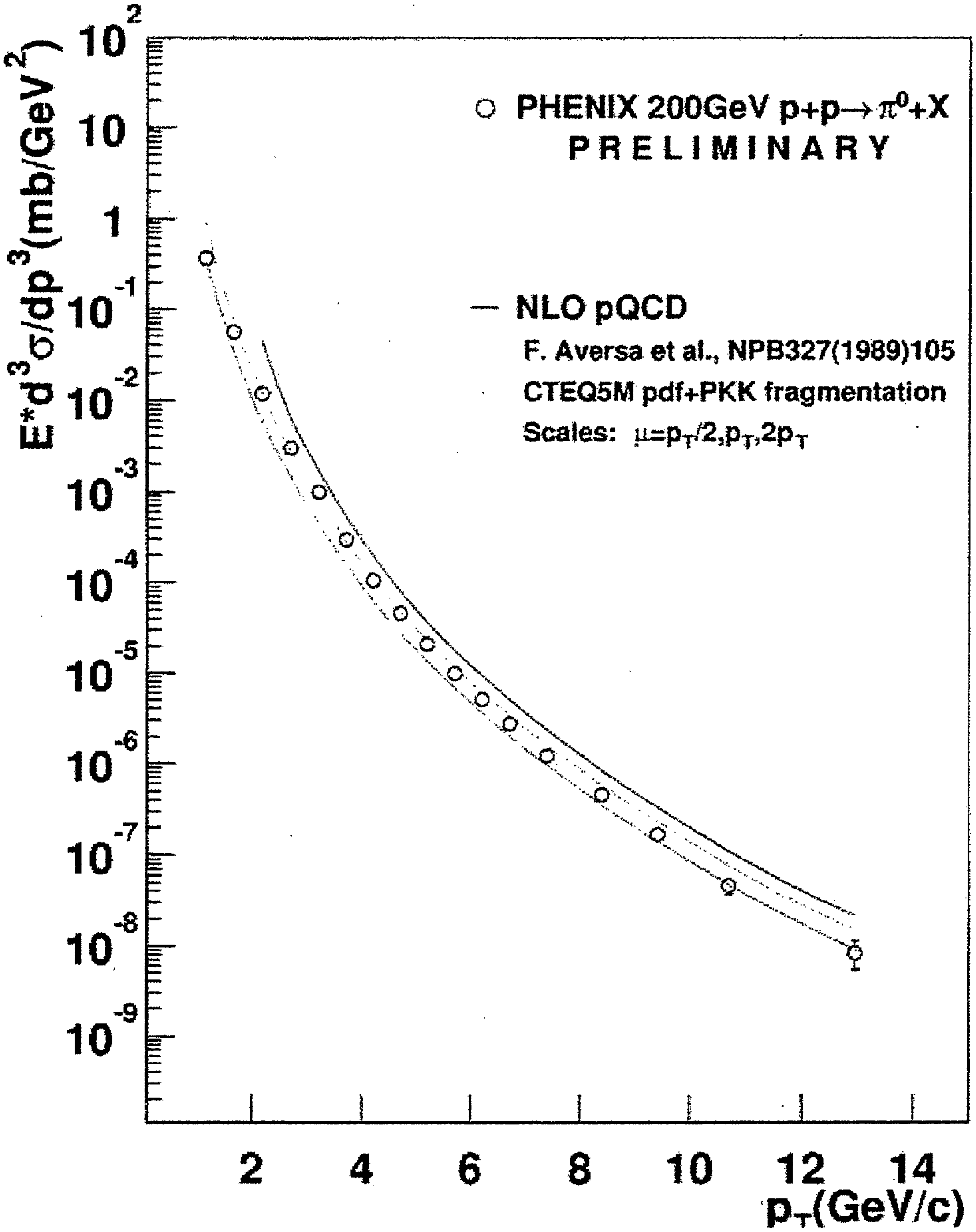
2003: π^0 as a jet surrogate to observe/measure/constrain gluon polarization.

$\sqrt{s} = 200$

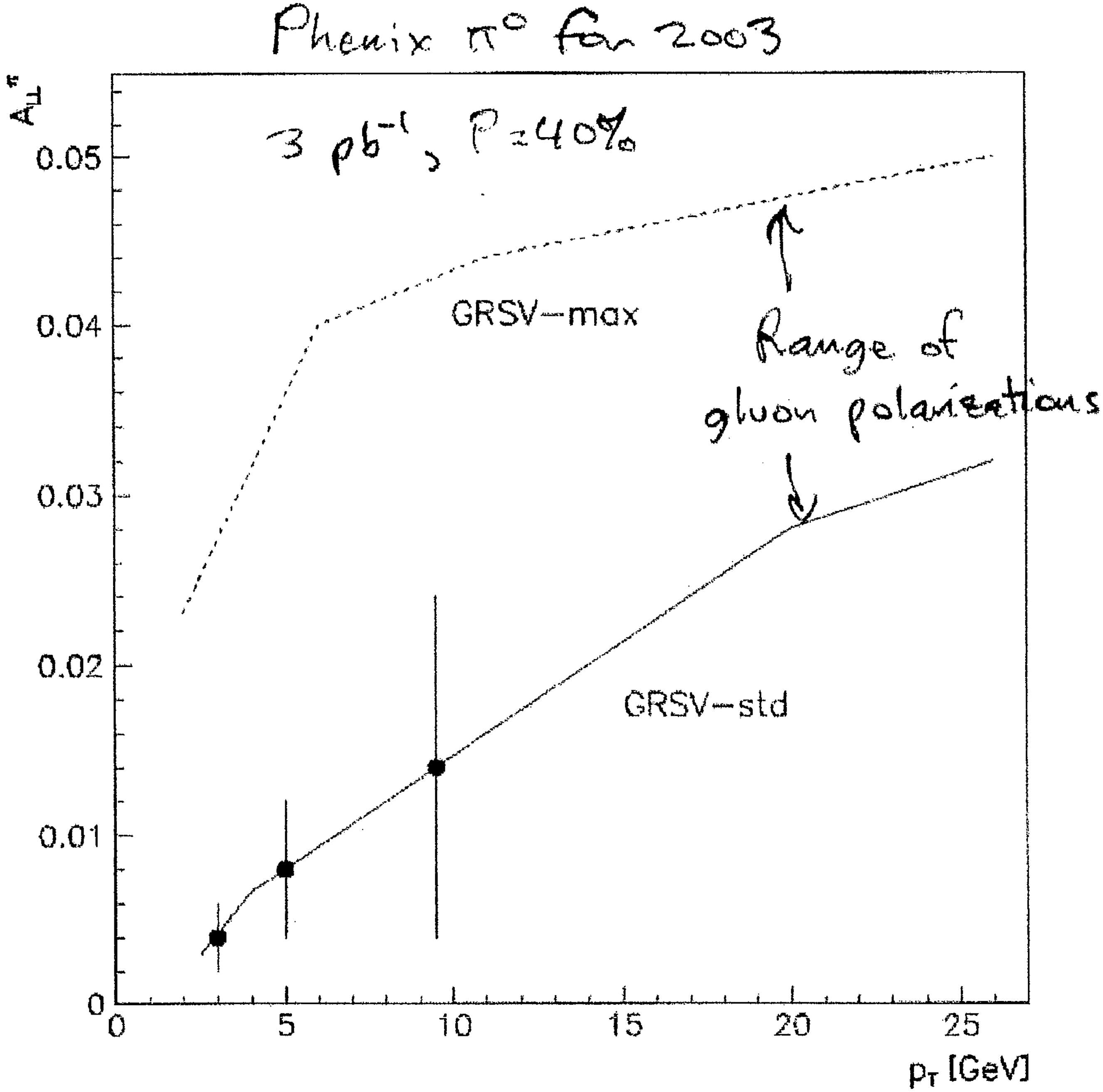


PHENIX π0 Reconstruction





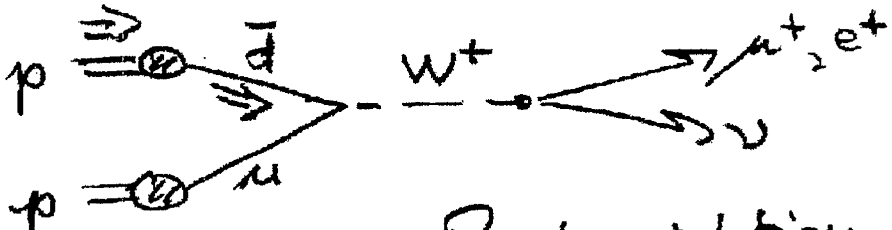
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E^*d^3\sigma/dp^3(mb/GeV^2)$
PHENIX 200GeV $p+p \rightarrow \pi^0+X$
PRELIMINARY
NLO pQCD
F. Aversa et al., NPB327(1989)105
CTEQ5M pdf+PKK fragmentation
Scales: $\mu=p_T/2, p_T, 2p_T$
2
4
6
8
10
12
14
p_T(GeV/c)



Phenix π° for 2003
3 pb⁻¹, P=40%
A_{LL}^{π}
0.05
0.04
0.03
0.02
0.01
0
GRSV−max
Range of gluon polarizations
GRSV−std
0
5
10
15
20
25
p_T [GeV]

Probes (cont.)

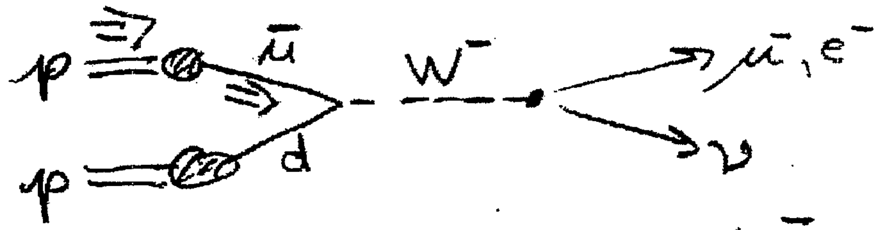
Quark polarization by flavor



Parity violation of W production

$A_L \approx \dfrac{\Delta \bar{d}}{\bar{d}}$ for W^+ backward from polarized p

$A_L \approx \dfrac{\Delta u}{u}$ for forward W^+



$A_L \approx \dfrac{\Delta \bar{u}}{\bar{u}}$ for W^- backward.

$A_L \approx \dfrac{\Delta d}{d}$ for W^- forward.

Search for new physics using parity violation

From M. Tannenbaum:

Criteria for The Maximum Discovery Potential:

- Look where most theorists predict that nothing will be found.
- Look in a channel where the known rates from conventional processes are small, since low background implies high sensitivity for something new.
- Be the first to explore a new domain—something that has never been measured by anybody else.

Almost any model for new physics violates parity since any new mass scale $\Lambda > M_W$.

Example: CDF search for quark substructure in high p_T jet production...

What will we learn from all of this?

① $\Delta q + \Delta\bar{q}$ small – DIS ✓

② $\frac{\Delta G}{G}$ small $\Rightarrow$ L_{orbit} large (!?)

large $\Rightarrow$ why? (T.P. Lee: connection to confinement $\Downarrow$ violates chirality)

③ $\Delta\bar{q}$ small – expected naively

large $\Rightarrow$ why? (Chiral quark soliton model?)

④ $\Delta\bar{u} = \Delta\bar{d}$ – naively expected

$\gg \Delta\bar{d}$ – CQSM; why?

$\ll \Delta\bar{d}$ $\Rightarrow$ why?

$\bar{d} \gg \bar{u}$ known why?

⑤ beyond standard model (quark substructure, Z', ...)

⑥ DIS + RHIC (+ EIC)

$\Rightarrow$ comprehensive tests of factorization, universality of structure functions, scales, ...

USING SPIN TO EXPLORE NUCLEON STRUCTURE AND QCD

Werner Vogelsang
RIKEN BNL Research Center
and
Brookhaven National Laboratory

Using Spin to Explore Nucleon Structure and QCD

Werner Vogelsang

RIKEN-BNL Research Center / BNL Nuclear Theory

RBRC/CCAST Symposium – April 7, 2003

Outline :

- Prologue
- Quark and Gluon Structure of the Nucleon
- Deeply-Inelastic Scattering
- Lessons from Polarized DIS
- A New Era of QCD Spin Physics
  - Gluon polarization in the nucleon
  - Learning about quark polarizations by flavor
  - Access to orbital angular momentum ?
  - Phenomena with transverse spin, Transversity
  - Using RHIC-Spin to find physics beyond the Standard Model ?

QCD – Theory of the strong interactions

confinement

hadronic structure

χSB

⋮

asymptotic freedom

perturbative theory

tool for exploring
new physics
& its backgrounds

Faces of a rich quantum field theory ! $\mathcal{L} = \bar{q}\,(i\not{D} - m)\,q - \frac{1}{4} G^{a}_{\mu\nu}\, G^{\mu\nu}_{a}$

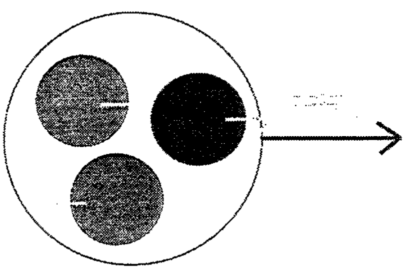
Recurring main theme of today's talk :

make use of perturbative $\longleftrightarrow$ non-perturbative interplay

- probe "our constituents" with weakly interacting quanta of asymptotic freedom
- test (and learn about) QCD spin interactions

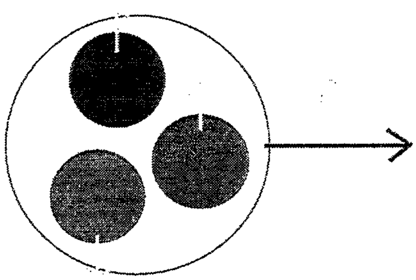
The Nucleon is composite : $\vec{\mu}_p = \frac{e\hbar}{mc}\, 2.79\; \vec{s}_p$

(Stern, 1933)

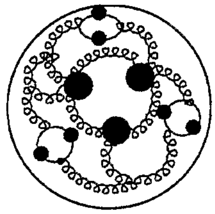


- $\mu_n/\mu_p = -2/3$ vs. $(\mu_n/\mu_p)_{\mathrm{exp}} = -0.685$ ✓
- $S_q = S_u + S_d = \frac{2}{3} - \frac{1}{6} = \frac{1}{2}$

- relation between proton spin and parton spins in QCD ?
- longitudinal vs transverse spin ?



In QCD :



Trying to "understand" the nucleon – what are the objectives ?

- describe in terms of matrix elements of quark and gluon operators

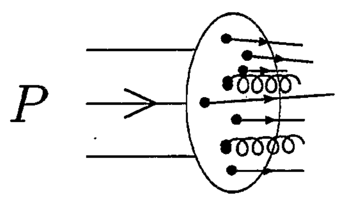
$$\langle N \,|\, \mathcal{O}_{q,g} \,|\, N \rangle$$

- know their physics interpretation
- find physical observables that give access to such matrix elements
  be able to predict such observables (pert. QCD, factorization theorems)
- measure these and determine matrix elements
- comparison to models of the nucleon, lattice gauge theory ?
- finally, use as tool to find physics beyond the Standard Model ?

I. Quark and Gluon Structure of the Nucleon

What's interesting to know ?

Nucleon moving fast in 3-direction. Suppose we could take a snapshot :



$p_i^+ \approx x_i P^+ \qquad (P^+ = P_0 + P_3)$

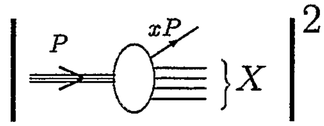
How many constituents with momentum between xP and $(x + dx)P$?

$$dx \int d^2\mathbf{k}_\perp \, \langle P \,|\, b^\dagger(xP, \mathbf{k}_\perp)\, b(xP, \mathbf{k}_\perp) \,|\, P \rangle$$

(for each parton species, $u, \bar{u}, d, s, \ldots, g$)

• let's take one quark type. With some footwork, this becomes

$$q(x) = \sum\!\!\!\!\!\!\int_X$$

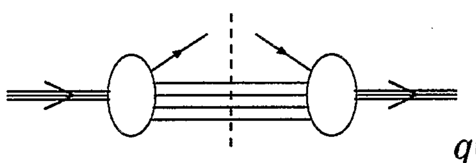


• probability density for finding a quark with momentum fraction x

• the formal expression is

$$q(x) = \sum\!\!\!\!\!\!\int_X \delta(P_X^+ - (1-x)P^+) \left| \langle X \,|\, \psi_+(0) \,|\, P \rangle \right|^2$$

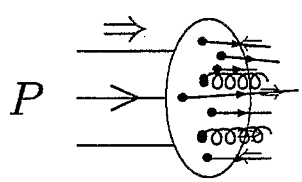
• with completeness of X



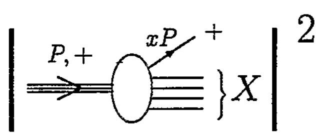
$$q(x) \sim \int dy^- \, e^{iy^- x} \, \langle P \,|\, \overline{\psi}_+(y^-) \, \psi_+(0) \,|\, P \rangle$$

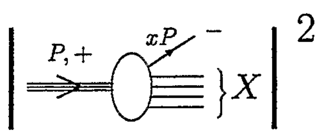
Nucleon and its constituents have spin.

Let's consider nucleon with positive helicity

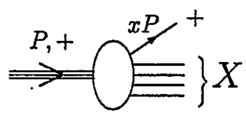


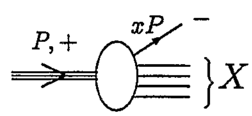
• How many constituents have same helicity ? Opposite ?



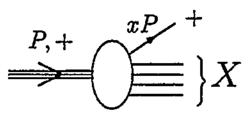


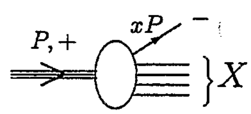
Combine

$q(x) = \Big|$ 

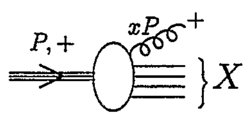
$\Big|^2 + \Big|$ 

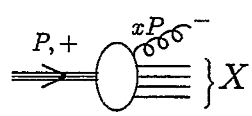
$\Big|^2$

$\Delta q(x) = \Big|$ 

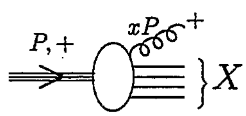
$\Big|^2 - \Big|$ 

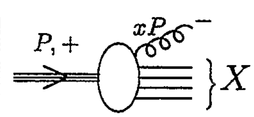
$\Big|^2$

$g(x) = \Big|$ 

$\Big|^2 + \Big|$ 

$\Big|^2$

$\Delta g(x) = \Big|$ 

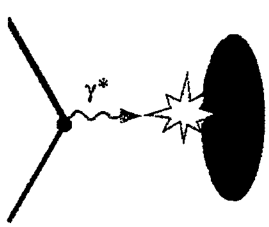
$\Big|^2 - \Big|$ 

$\Big|^2$

How to measure this ?

Answer : They can be seen in very inelastic reactions

II. The archetype : Deeply-Inelastic scattering



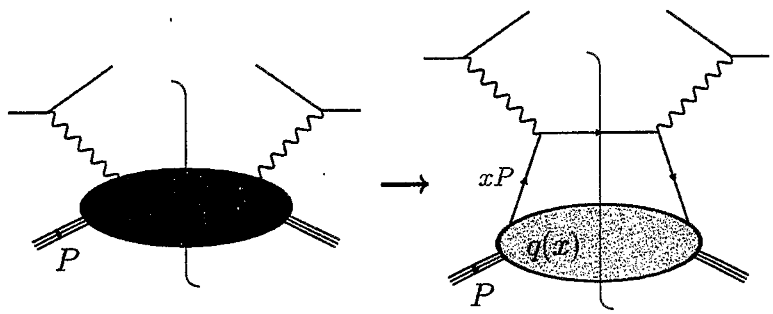
highly virtual photon, $Q^2 \gg m_N^2$

cross section: $\sim \underbrace{\mathcal{L}_{\mu\nu}(k,q,s)}_{\text{leptonic}} \cdot \underbrace{\mathcal{W}^{\mu\nu}(P,q,S)}_{\text{hadronic}}$

$$\begin{aligned}
\mathcal{W}^{\mu\nu}(P,q,S) \;=\; & \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_1(x,Q^2) \\
& + \left(P^\mu - \frac{P\cdot q}{q^2} q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2} q^\nu\right) F_2(x,Q^2) \\
& + i\, M_N\, \varepsilon^{\mu\nu\rho\sigma} q_\rho \left[\frac{S_\sigma}{P\cdot q}\, g_1(x,Q^2) + \frac{S_\sigma(P\cdot q) - P_\sigma(S\cdot q)}{(P\cdot q)^2}\, g_2(x,Q^2)\right]
\end{aligned}$$

Large Q^2 : γ^* takes snapshot of nucleon

$\Rightarrow$ "parton model" (Feynman; Bjorken,Paschos)



$\Rightarrow$ can calculate structure functions in terms of quark distributions :

$$F_1(x) \;=\; \frac{1}{2}\sum_q e_q^2\,[\,q(x) + \bar{q}(x)\,]$$

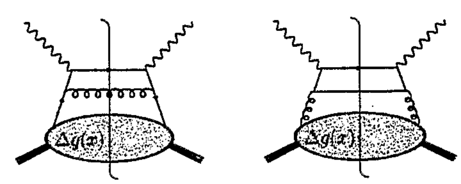
$$g_1(x) \;=\; \frac{1}{2}\sum_q e_q^2\,[\,\Delta q(x) + \Delta\bar{q}(x)\,]$$

Scaling behavior !

How does this hold up in full QCD ? – A success story !

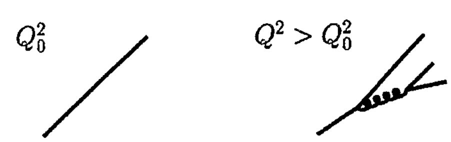
$$g_1(x,Q^2) = \sum_q e_q^2\,[\,\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\,]\,[1 + \mathcal{O}(\alpha_s)] + \mathcal{O}(\alpha_s)\Delta g(x,Q^2) + \mathcal{O}\left(\frac{\lambda^2}{Q^2}\right)$$

- QCD corrections to Parton Model : typically from



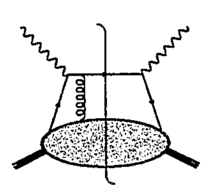
leading effect : DGLAP evolution of quark distributions

$Q^2 \leftrightarrow$ resolving power of probe



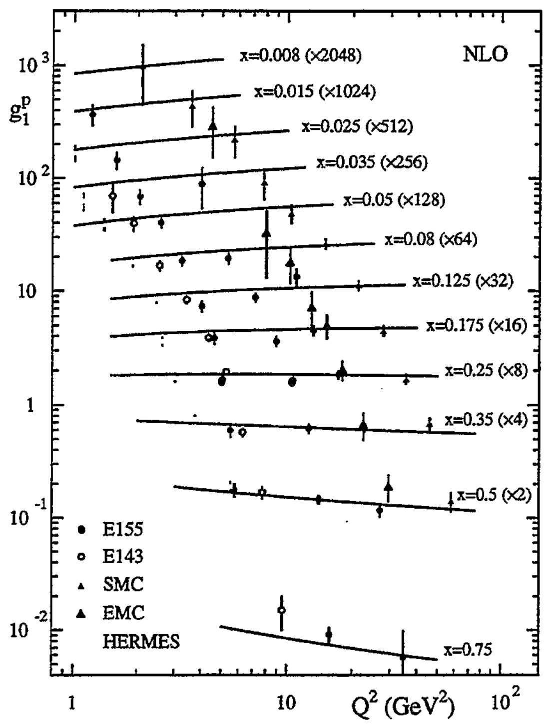
Direct predictions of QCD !

- Power-suppressed contributions $\rightsquigarrow$ small



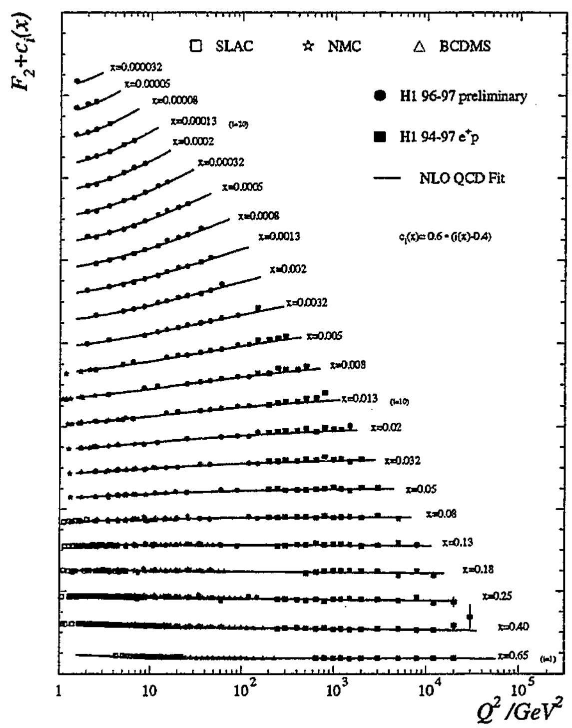
World data on pol. and unpol. deep-inelastic scattering

polarized



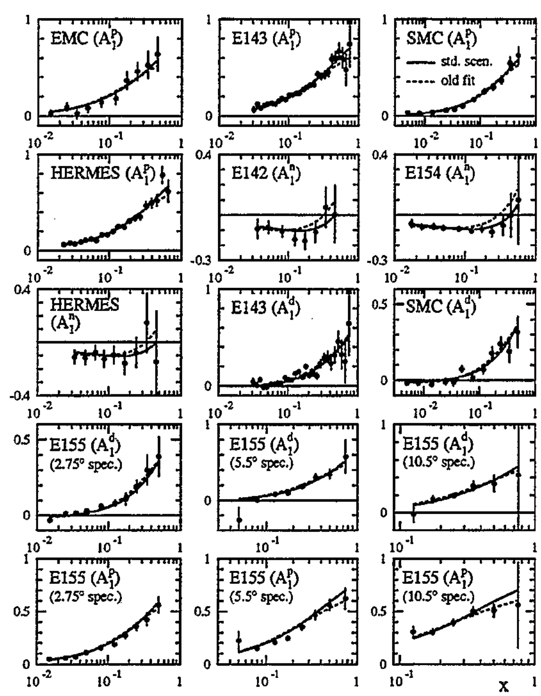
NLO QCD fit: Glück, Reya, Vogelsang, MS (2000 update)

unpolarized



III. Lessons from Polarized DIS

Several generations of beautiful fixed-target experiments at SLAC, CERN, DESY



(Glück, Reya, Stratmann, WV NLO QCD fit)

- a strong interest in total polarizations :

$$\Delta Q = \int_0^1 \Delta q(x,Q^2)\,dx = \int_0^1 \left[q^+(x,Q^2) - q^-(x,Q^2)\right] dx$$

Why ?

- measures $2\,S_q$ $\rightsquigarrow$ access to quark spin contribution to nucleon spin !
- it turns out they are related to matrix elements of axial currents :

$$s^\mu\,\left[\Delta Q + \Delta\bar{Q}\right] = \langle P,S\,|\,\bar{\psi}_q\,\gamma^\mu\,\gamma^5\,\psi_q\,|\,P,S\rangle$$

- such currents occur in weak interactions
- example : neutron β decay

$$g_A \propto \langle p\,|\,\bar{\psi}_u\,\gamma^\mu\,\gamma^5\,\psi_d\,|\,n\,\rangle$$

- $\rightsquigarrow$ deep connections between hadronic and DIS physics   Bjorken

Bjorken's sum rule

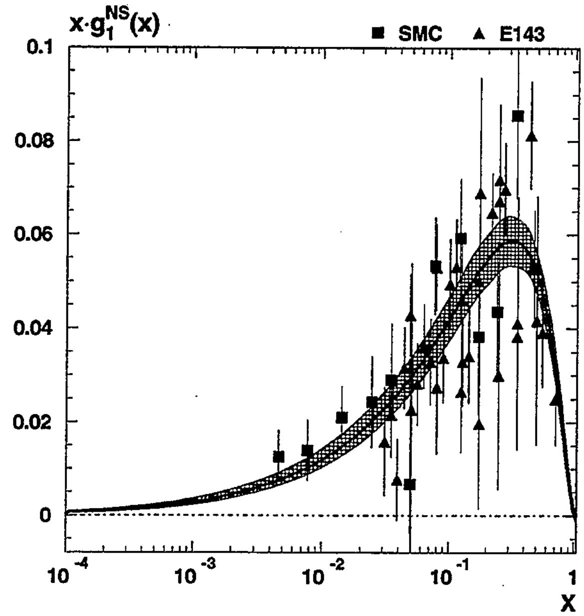
- originally, a main motivation for measuring g_1 !

$$\boxed{\int_0^1 dx\left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] = \tfrac{1}{6}\;\underset{\uparrow\; n\,\to\,p\,e^-\,\bar{\nu}_e}{g_A}\left[\,1 + \mathcal{O}(\alpha_s)\,\right]}$$

- today, we know :

$$"\mathcal{O}(\alpha_s)" = -\frac{\alpha_s}{\pi} - \left[\frac{55}{12} - \frac{n_f}{3}\right]\left(\frac{\alpha_s}{\pi}\right)^2 - \left[41.4 - 7.6\,n_f + \frac{115}{648}\,n_f^2\right]\left(\frac{\alpha_s}{\pi}\right)^3 \pm \ldots$$

(Kodaira et al.; Gorishny,Larin; Larin,Vermaseren)



$Q^2 = 5$ GeV^2 :

Theory :

$$\text{S.R.} = 0.181 \pm 0.003$$

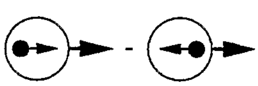
SMC : (E155 similar)

$$\text{S.R.} = 0.174 \pm 0.005 \begin{array}{cc} +0.011 & +0.021 \\ -0.009 & -0.006 \end{array}$$

- more precision in the future ? $\rightsquigarrow$ eRHIC

The striking finding :

Quarks do not carry the proton spin !



$$\Delta\Sigma \equiv \Delta\mathcal{U} + \Delta\bar{\mathcal{U}} + \Delta\mathcal{D} + \Delta\bar{\mathcal{D}} + \Delta\mathcal{S} + \Delta\bar{\mathcal{S}} \approx 0.2 \ll 1$$

- certainly not predicted by constituent quark models :

e.g., simplest case $\quad |P\rangle = \frac{1}{\sqrt{18}}\left[2u^\uparrow u^\uparrow d^\downarrow - u^\uparrow u^\downarrow d^\uparrow - u^\downarrow u^\uparrow d^\uparrow + \text{perm.}\right]$

$$\Rightarrow 2\,S_u = 4/3\ ,\ \ 2\,S_d = -1/3 \quad \rightsquigarrow \quad \boxed{S_q = S_u + S_d = \frac{1}{2}}$$

- some potential pitfalls :
  - needs low-x extrapolation (eRHIC...)
  - low x usually have low Q^2 (eRHIC...)
  - relies on information from hyperon β decays

- a crucial feature of the quark singlet :

$$s^\mu \, \Delta\Sigma \;=\; \langle P, S \mid \underbrace{\bar{\psi}\,\gamma^\mu\,\gamma^5\,\frac{1\!\!1}{2}\,\psi}_{\text{singlet axial current } j_5^{\mu,0}} \mid P, S\rangle$$

- deep connection to axial anomaly :

$$\partial_\mu\, j_5^{\mu,0} \equiv \partial_\mu\left[\bar{\psi}\,\gamma^\mu\,\gamma^5\,\psi\right] = n_f\,\frac{\alpha_s}{2\pi}\,\epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\left[G_{\mu\nu}\,\tilde{G}^{\mu\nu}\right]$$

- a consequence (in $\overline{\mathrm{MS}}$ scheme) :

$$\Delta\Sigma(Q^2) \;=\; \left(1 \;+\; \frac{6n_f}{(33-2n_f)\,\pi}\;\left[\,\alpha_s(Q^2)\;-\;\alpha_s(\mu_0^2)\,\right]\right)\;\Delta\Sigma(\mu_0^2)$$

$\Rightarrow$ moderate decrease in perturbative region (Jaffe)

- connection with gluon spin contribution ?

What else may carry the proton spin ?

$$\frac{1}{2} \;=\; \langle P,\frac{1}{2}\mid \int d^3x\;\left[x^1\,T^{02}(x)\;-\;x^2\,T^{01}(x)\right]\mid P,\frac{1}{2}\rangle$$

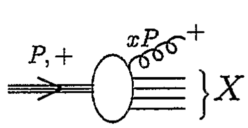
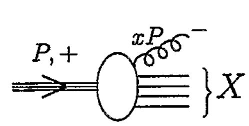
One finds (Jaffe,Manohar; Ji)

$$M_{012} \;=\; \underbrace{\bar{\psi}\,\gamma^3\gamma_5\,\psi}_{\sim\ \text{quark spin}} \;+\; \underbrace{\psi^\dagger\left(\vec{x}\times\left(-i\vec{D}\right)\right)_3\psi}_{\sim\ \text{quark OAM}} \;+\; \underbrace{\left(\vec{E}\times\vec{A}\right)_3}_{\text{gluon spin}} \;+\; \underbrace{E_j\left(\vec{x}\times i\vec{D}\right)_3 A_j}_{\text{gluon OAM}}$$

leads to

$$\tfrac{1}{2} \;=\; \tfrac{1}{2}\Delta\Sigma \;+\; \Delta G \;+L_q \;+\; L_g$$

- Perhaps gluons ? $\Delta G(Q^2) \;=\; \int_0^1 dx\,\Delta g(x,Q^2)$ where

$\Delta g(x) \;=\; \Bigg|$  $\Bigg|^2 \;-\; \Bigg|$  $\Bigg|^2$

- Orbital angular momentum ?

IV. A New Era of QCD Spin Physics

- excitement from polarized DIS has led to
  - new generation of facilities to explore the nucleon spin structure
  - large theoretical activity
- key goals :
  - gluon polarization in nucleon
  - more information on quark densities, by flavor
  - orbital angular momentum
  - transverse polarization of quarks in a nucleon
  - . . .

RHIC will be the key player in most of this.
Information from lepton-nucleon scattering
will remain vital : HERMES, COMPASS, . . . , eRHIC

Probing gluon polarization Δg

- DIS : probes quarks and antiquarks
- Crucial observation : Parton distributions are universal !
  - the same distributions appear in hadron-hadron scattering (Sterman,Libby; Ellis et al.; Collins,Soper,Sterman; Collins)
  - makes notion of "nucleon structure" meaningful
- do polarized hadron-hadron scattering : RHIC !

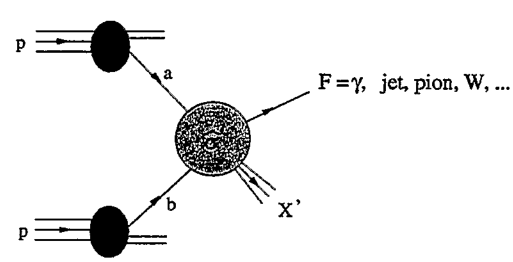
Examples :

- high-p_T reactions, $pp \to \text{jet}X$, $pp \to \gamma X$, $pp \to \pi X$, ...
- large produced masses, $pp \to (c\bar{c})X$

Hard scattering in hadron collisions

consider high-p_T final state : $\Rightarrow$ hard scale

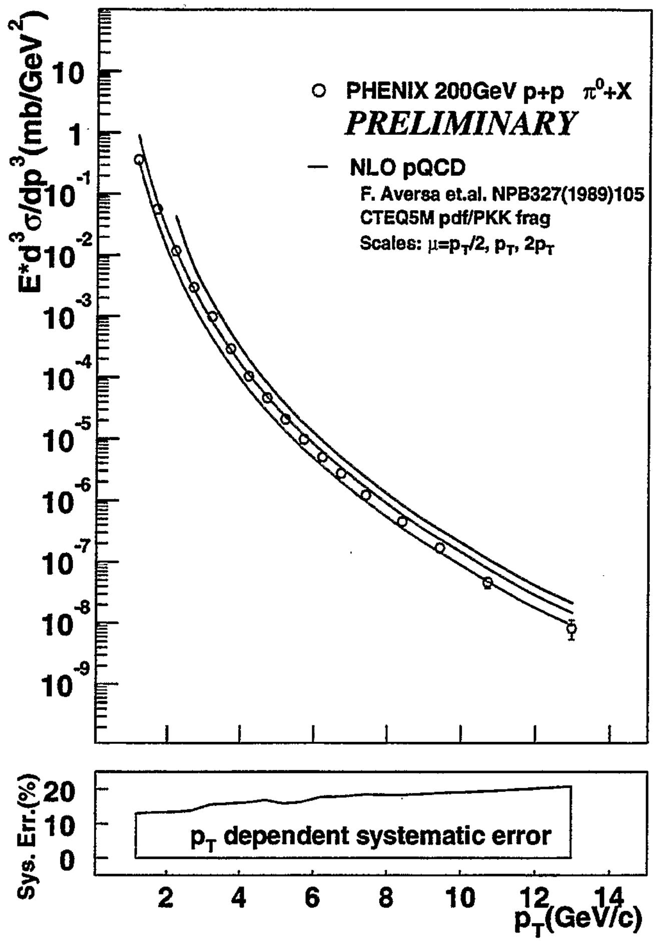
$$p_T^3 \frac{d\sigma}{dp_T} = \left| \quad \right|^2 + \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$



$$\boxed{\begin{aligned} p_T^3 \frac{d\sigma^{pp\to \mathrm{F}X}}{dp_T} &= \sum_{abc} \int dx_a\, dx_b\, dz_c\, f_a(x_a,\mu)\, f_b(x_b,\mu) \\ &\times p_T^3 \frac{d\hat{\sigma}^{ab\to \mathrm{F}X'}}{dp_T}(x_a P_a, x_b P_b, P^{\mathrm{F}}/z_c, \mu) \; + \; \text{Power corr.} \end{aligned}}$$

$pp \to \pi^0 X$ **by PHENIX**

($\pm$30% normalization unc.)



pQCD hard scattering works well at colliders !

- in all cases, it is crucial to know QCD corrections to hard scattering :

$$\hat{\sigma} = \underbrace{\hat{\sigma}^0}_{\text{LO}} + \underbrace{\alpha_s \hat{\sigma}^1}_{\text{NLO}} + \dots$$

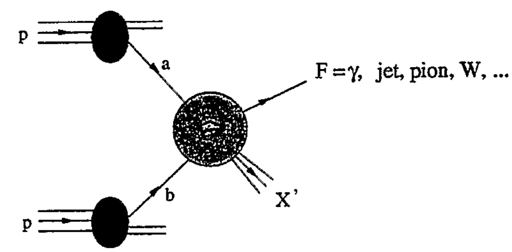
– often sizable

– reduce dependence on factorization scale μ

Hard scattering in polarized hadron collisions

spin asymmetry $\quad A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \equiv \frac{\Delta\sigma}{\sigma}$

$$p_T^3 \frac{d\Delta\sigma}{dp_T} = \left| \quad \right|^2 + \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$



$$p_T^3 \frac{d\Delta\sigma^{pp\to FX}}{dp_T} = \sum_{abc} \int dx_a \, dx_b \, dz_c \, \Delta f_a(x_a, \mu) \, \Delta f_b(x_b, \mu)$$
$$\times \, p_T^3 \frac{d\Delta\hat{\sigma}^{ab\to FX'}}{dp_T}(x_a P_a, x_b P_b, P^F/z_c, \mu) \; + \; \text{P.C.}$$

Excellent prospects for RHIC :

- a collider !
- several different reactions with sensitivity to Δg can be studied

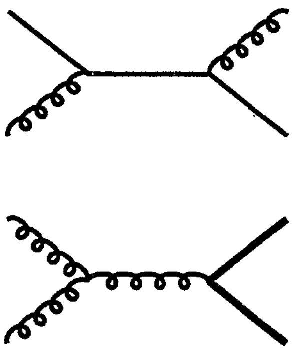
  for example, $pp \to \gamma X$, $pp \to \mathrm{jet}X$, $pp \to \pi X$, $pp \to (c\bar{c})X$, ...

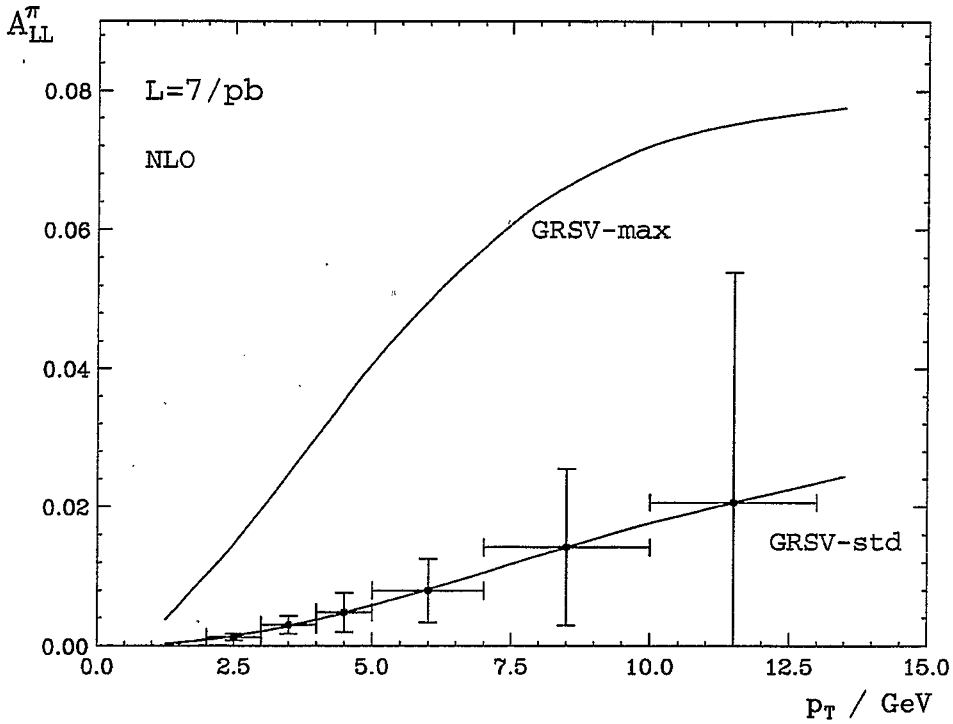
- for the first time, we can test universality properties of polarized pdfs
- emphasize : we are not only measuring nucleon structure

  – we also test QCD spin interactions !
- NLO corrections now known for *all* relevant reactions

  Gordon,WV; Contogouris et al.; de Florian,Frixione, Signer,WV; Stratmann,Bojak; de Florian; Jäger,Stratmann,WV, ...

Already in coming run : $\vec{p}\vec{p} \to \pi^0 X$ **Jäger,Stratmann,WV**





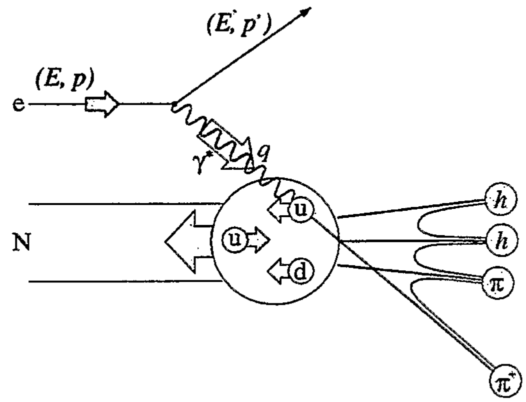
Further information on quark distributions

- inclusive DIS cannot distinguish between q and $\bar{q}$
- considerable interest :

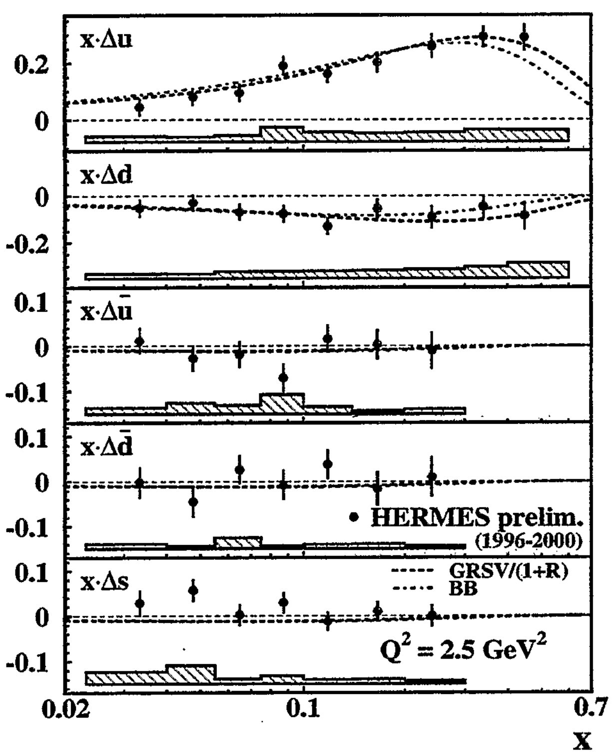
  SU(2) breaking in sea (pion cloud models, Pauli exclusion, . . .)

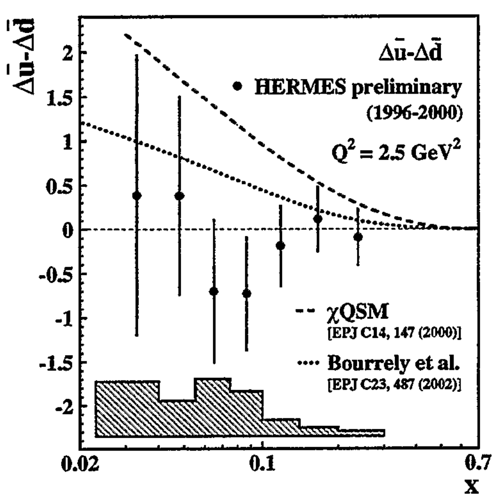
  (Thomas,Signal,Cao; Diakonov,Goeke,Weiss; Glück,Reya; Schäfer,Fries; Kumano; Wakamatsu; . . .)
- strange quark polarization

  (Ellis,Karliner; Brodsky et al.; Li,Zhang,Ma; . . .)
- one option : semi-inclusive DIS. Detect a hadron $h = \pi^+, \pi^-, K^\pm, \ldots$



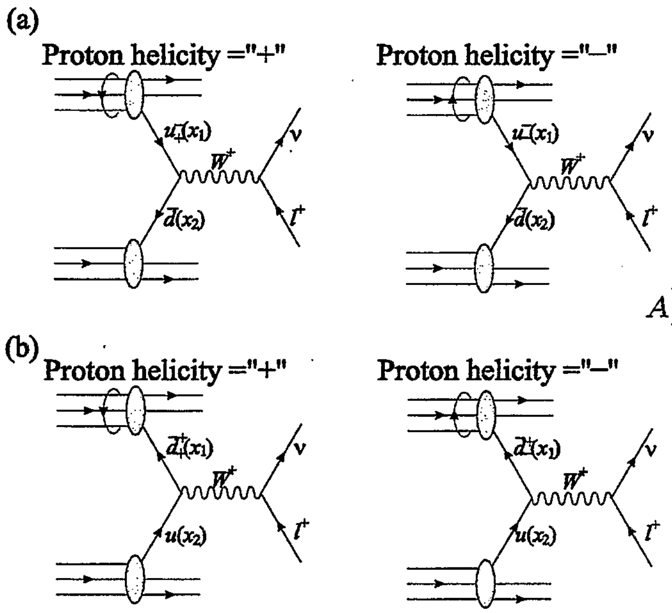
New HERMES results (Spin-2002) :





A neat way at RHIC : W production

Parity violation $\leftrightarrow$ W selects parton helicity !



$$A_L^W \equiv \frac{\sigma_-(W) - \sigma_+(W)}{\sigma_-(W) + \sigma_+(W)}$$

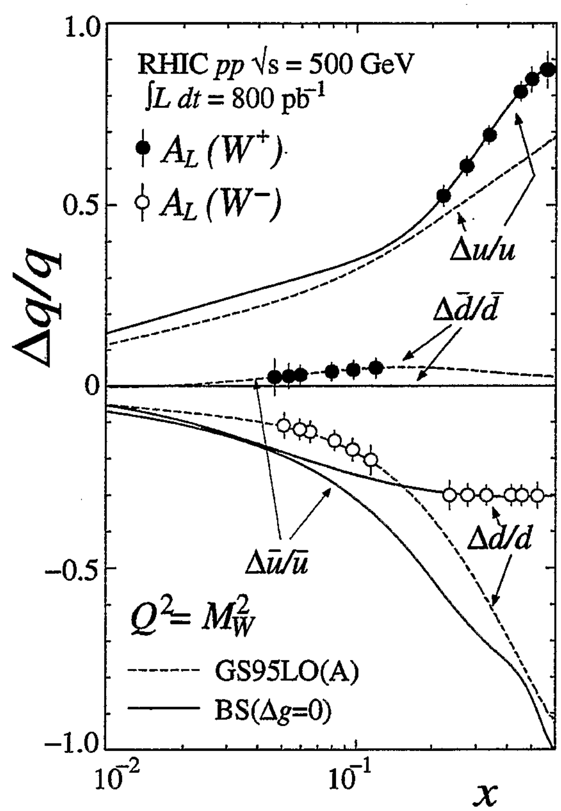
$$A_L^{W^+} \approx \frac{\Delta u(x_1)\, \bar{d}(x_2) - \Delta \bar{d}(x_1)\, u(x_2)}{u(x_1)\, \bar{d}(x_2) + \bar{d}(x_1)\, u(x_2)}$$

(Bourrely,Soffer)

What you get :

NLO corrections, acceptance issues :

Weber; Kamal; Gehrmann; Nadolsky,Yuan



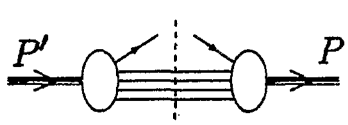
Accessing orbital angular momentum ?

- recall :

$$M_{012} = \underbrace{\bar{\psi}\gamma^3\gamma_5\psi}_{\sim \text{ quark spin}} + \underbrace{\psi^\dagger \left(\vec{x} \times \left(-i\vec{D}\right)\right)_3 \psi}_{\sim \text{ quark OAM}} + \underbrace{\left[\vec{x} \times \left(\vec{E}(\vec{x}) \times \vec{B}(\vec{x})\right)\right]_3}_{\sim \textit{ total} \text{ gluon ang. mom.}}$$

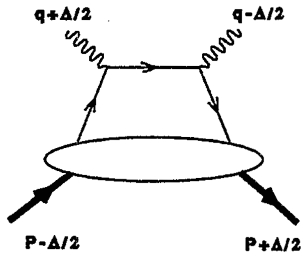
- Ji noted that the *total* angular momenta of quarks and gluons can be measured in "Deeply-virtual Compton scattering"
- the crucial point is that the $\vec{x}$ forces one off the forward direction
  - ordinary parton distribution : $q(x) \sim \int dy\, e^{iyx} \langle P \,|\, \overline{\psi}_+(y)\, \psi_+(0)\, |\, P\rangle$
  - off-forward parton distributions :

$$\begin{aligned} \int dy\, e^{iyx} \langle P' \,|\, \overline{\psi}_+(y)\, \psi_+(0)\, |\, P\rangle &= H(x,\xi,t)\; \left[\bar{U}(P')\, \gamma^+\, U(P)\right] \\ &+ E(x,\xi,t)\; \left[\bar{U}(P')\, \frac{i\sigma^{\mu+}\Delta_\mu}{2M}\, U(P)\right] \end{aligned}$$



$\Delta = P - P'\,,\;\; t = \Delta^2\,,\;\; \xi = \Delta^+$

- H and E are related to ordinary parton distributions, and to nucleon form factors
- Ji found a process that may be used to obtain the H and E, and to derive J_q :



$$J_q = \frac{1}{2} \lim_{\Delta^2 \to 0} \int dx\, x \left[H_q(x, \xi, \Delta^2) + E_q(x, \xi, \Delta^2) \right]$$

- much experimental activity HERA, HERMES, JLab,. . . , eRHIC
- evolution of total angular momentum :

$$\mu \frac{d}{d\mu} \begin{pmatrix} J_q(\mu) \\ J_g(\mu) \end{pmatrix} = \frac{\alpha_s(\mu)}{\pi} \frac{1}{9} \begin{pmatrix} -16 & 3n_f \\ 16 & -3n_f \end{pmatrix} \begin{pmatrix} J_q(\mu) \\ J_g(\mu) \end{pmatrix}$$

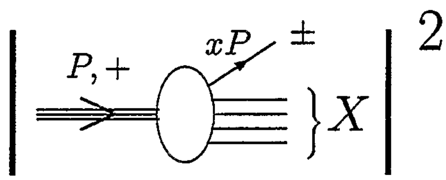
$$J_q(\infty) = \frac{1}{2} \frac{3n_f}{16 + 3n_f}, \quad J_g(\infty) = \frac{1}{2} \frac{16}{16 + 3n_f}$$

- the nucleon becomes very simple asymptotically !

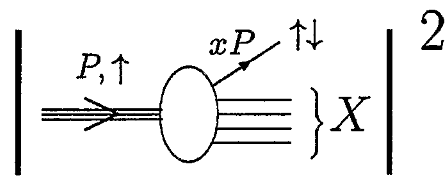
Phenomena with transverse spin – 1 :

Transversity

Recall : a helicity parton distribution

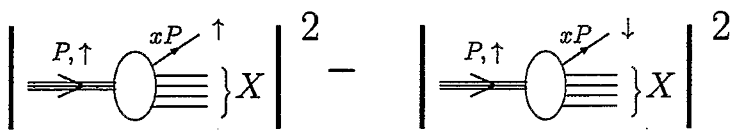


How about the same for transverse spin ?



Indeed, this is a new parton distribution – transversity

$\delta q(x) =$

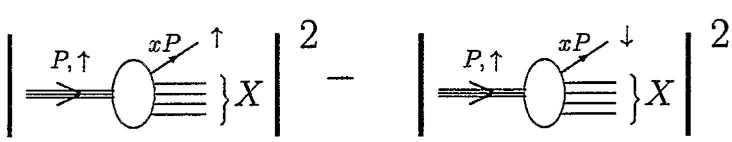


Transverse spin may be described in helicity basis :

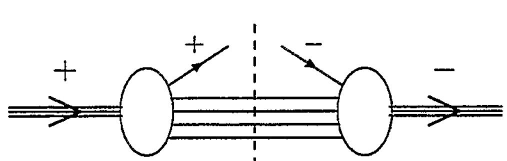
$$|\perp\rangle = \frac{1}{\sqrt{2}}\Big(|+\rangle + i\,|-\rangle\Big) \qquad |\top\rangle = \frac{1}{\sqrt{2}}\Big(|+\rangle - i\,|-\rangle\Big)$$

But then :

$\delta q(x) =$



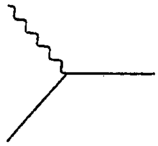
$\propto$



"Helicity flip" !

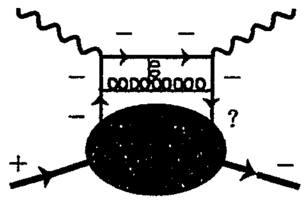
Not possible for gluons

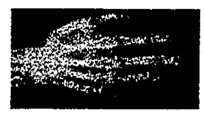
* electroweak probes preserve chirality ($\approx$ helicity)



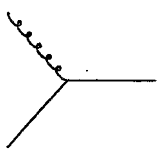
$$\gamma,\, W^{\pm},\, Z^0 : \quad \begin{cases} \bar{\Psi}\gamma^\mu\Psi = \bar{L}\gamma^\mu L + \bar{R}\gamma^\mu R \\ \bar{\Psi}\gamma^\mu\gamma^5\Psi = \bar{L}\gamma^\mu L - \bar{R}\gamma^\mu R \end{cases}$$

$\Rightarrow$ not accessible in incl. DIS :





* hard QCD probes also preserve chirality :



$$\bar{\Psi}\gamma^\mu\frac{\lambda}{2}\Psi = \bar{L}\gamma^\mu\frac{\lambda}{2}L + \bar{R}\gamma^\mu\frac{\lambda}{2}R$$

So . . .

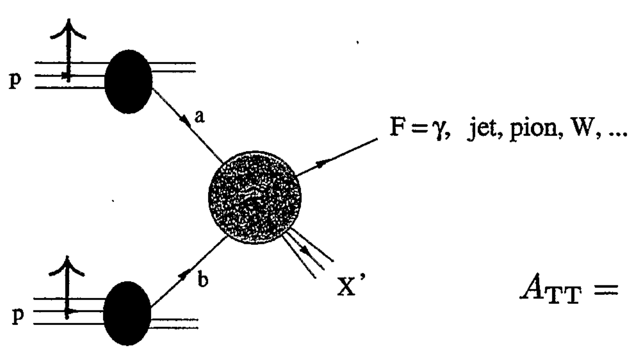
* how can transversity be non-zero in the first place ?

parton distributions involve non-perturbative physics, where chiral symmetry is broken !

* how to measure ?

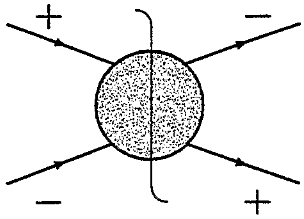
RHIC will allow access to transversity !

One (of several) ideas : hard scattering of two transversely polarized protons



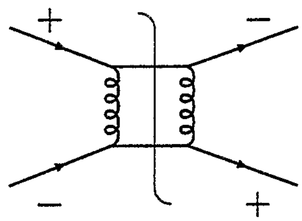
$$A_{\mathrm{TT}} = \frac{d\sigma^{p^\uparrow p^\uparrow} - d\sigma^{p^\uparrow p^\downarrow}}{d\sigma^{p^\uparrow p^\uparrow} + d\sigma^{p^\uparrow p^\downarrow}}$$

- why ? A_{TT} allows in partonic scattering

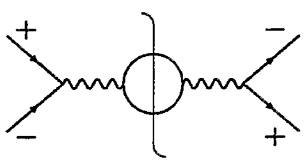


$$A_{\mathrm{TT}} \;\propto\; \cos(2\varphi)\,\mathrm{Re}\left[\, h_{+-;\dots}\;\; h^{*}_{-+;\dots} \,\right]$$

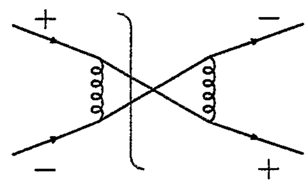
- not in



- however, two possibilities :



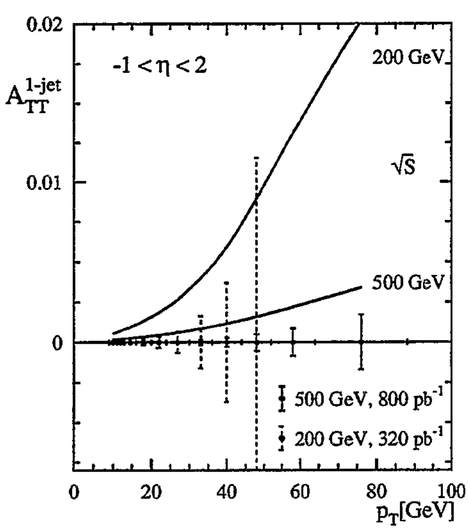
Drell-Yan, direct photons



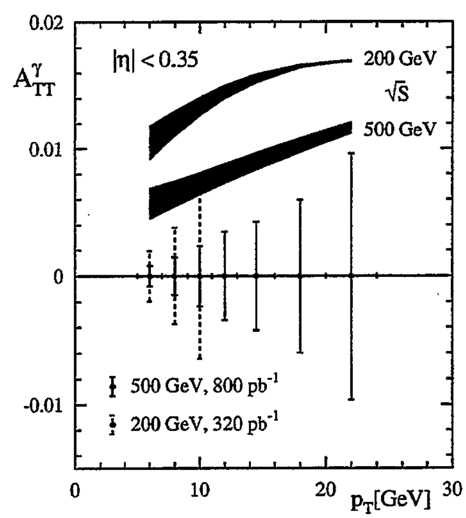
jet production (id. quarks)

Predictions : $\boxed{A_{\mathrm{TT}} \ll A_{\mathrm{LL}}}$

1-jet
STAR



high-p_T photon
PHENIX



(Jaffe,Saito; Soffer,Stratmann,WV)

Phenomena with transverse spin – 2 :

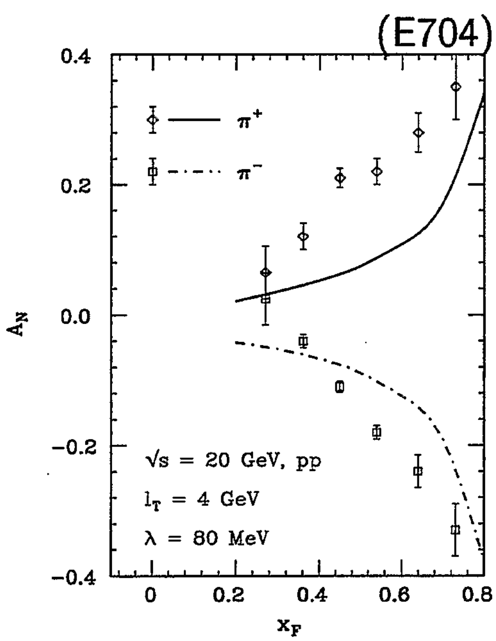
Single transverse-spin asymmetries

$p(\uparrow\downarrow) + p \to C + X$ with C '=' high-p_T π, γ, . . .

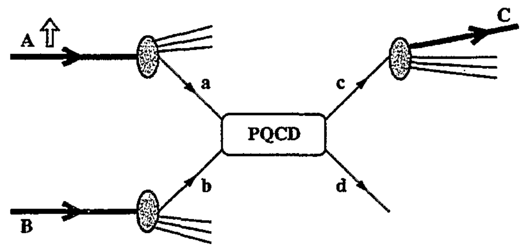
$A_N \equiv \dfrac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$ correlation $\sim i\vec{s}_T \cdot (\vec{p} \times \vec{l})$

fixed-target experiments at
BNL,ANL,Fermilab,. . . : A_N large !

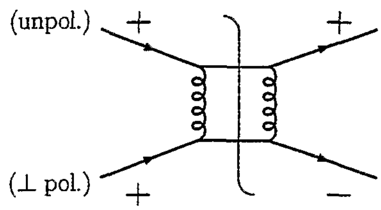
$p^\uparrow p \to \pi X$



• In "Parton Model" ?



• partonic scattering



$$A_{\rm N} \;\propto\; \sin(\varphi)\,{\rm Im}\left[\,h_{++;\ldots}\;h^*_{+-;\ldots}\right]$$
$$\propto\; {\rm Im}\{({\rm helicity\ non-flip})\,({\rm single\ flip})^*\} \;=\; 0$$

• can only arise as $\frac{m_q}{p_T}\alpha_s \ll 1$ (Kane,Pumplin,Repko)

• the lesson : $A_{\rm N}$ is *power-suppressed* (albeit large . . .)

• in pQCD, it has to behave as $1/p_T$ at large p_T

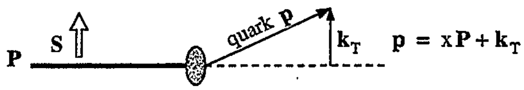
• large-x_F measurements of $A_{\rm N}$ open the window

• there is more dynamics in QCD that can lead to power-suppressed contributions

• intrinsic transverse momenta, quark-gluon correlations

- $k_\perp$-dependence of distribution/fragmentation fcts.

  Sivers; Collins; Boer; Anselmino, Mulders et al.; Leader et al. . . .



asymmetry $\boxed{q_{p\uparrow}(x,\vec{k}_T) \neq q_{p\uparrow}(x,-\vec{k}_T)}$

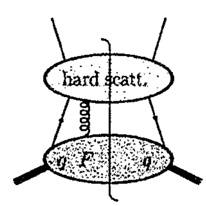
- interplay with steeply falling cross section
- much interest in k_T dependent quark distribution :

$$q(x,\vec{k}_T) \sim \int dy^- \, d^2y_T \, \mathrm{e}^{iy^- x + i\vec{k}_T\cdot\vec{y}_T} \, \langle P \,|\, \overline{\psi}_+(y^-,\vec{y}_T) \; \psi_+(0) \;|\, P\rangle$$

  T-invariance of QCD appears to forbid a correlation $\vec{S}_T \cdot (\vec{P} \times \vec{k}_T)$

- recent development : gauge links that make pdfs *gauge invariant* allow the "T-odd" structure (Brodsky,Hwang,Schmidt; Collins; Belitsky,Ji,Yuan)

- "Twist-3 quark-gluon correlation functions"



  Efremov,Teryaev; Qiu,Sterman; Koike et al.; . . .

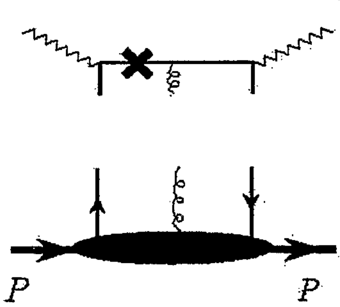
- Qiu,Sterman prove factorization for A_{N} to $1/Q$ power in QCD

  $\Rightarrow$ new universal nucleon matrix elements $\sim \langle P|\,\bar{q}\,F\,q\,|P\rangle$

- we are beginning to understand the similarities :

phase in hard-scattering

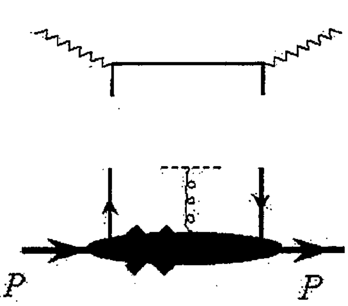
(Efremov,Teryaev;Qiu,Sterman)



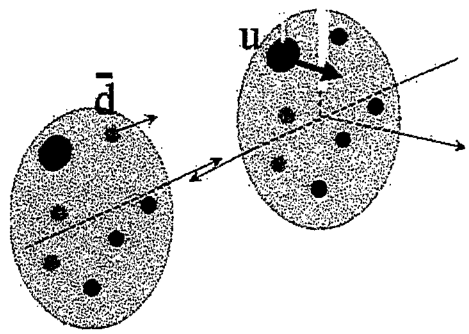
(Belitsky; Qiu; Boer,Mulders,Pijlman)

phase in distribution function

(Sivers; Anselmino et al.; Collins; Boer et al.)



- a caveat :
  - data on $A_{\rm N}$ in "borderline pQCD" regime $p_T \sim \mathcal{O}(1)$ GeV
- in "soft regime", description for $A_{\rm N}$ could be different : (Boros,Liang,Meng)
- quark-antiquark fusion "on front surface"

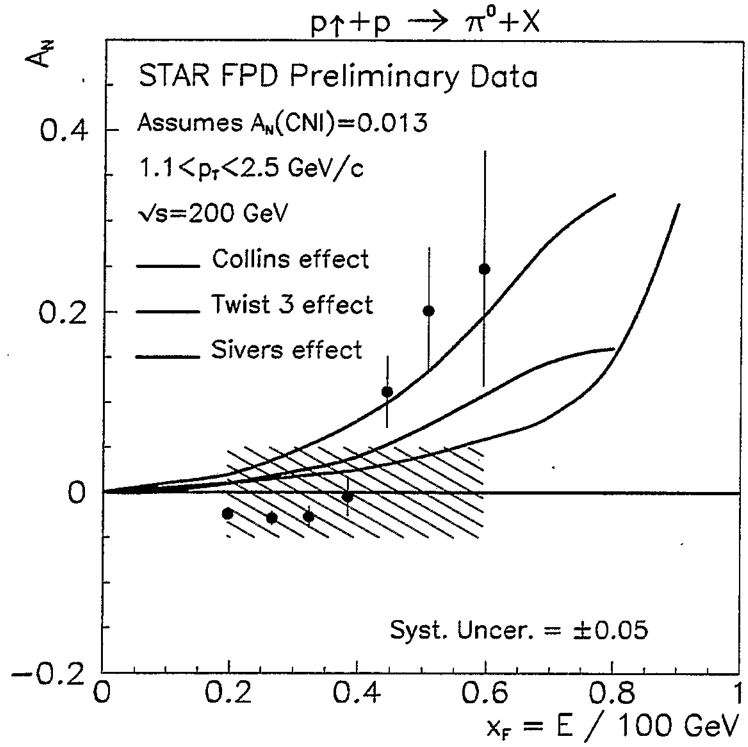


- same physics in different language ?
- recent development :
  Fourier transforms of off-forward parton distributions give information on position space distribution of partons

$$q(x,\vec{b}_T) = \int d^2\Delta_T \, e^{-i\vec{\Delta}_T \cdot \vec{b}_T} \, H(x,0,-\Delta_T^2)$$

(Burkardt; Ralston,Pire; Diehl)

- for transverse nucleon polarization : expect distortion
- may lead to $A_{\rm N}$ asymmetry
- connection between $q(x,\vec{b}_T)$ and $q(x,\vec{k}_T)$ (Burkardt)
- we are learning more from ep (HERMES,eRHIC) . . .
  . . . AND from RHIC !



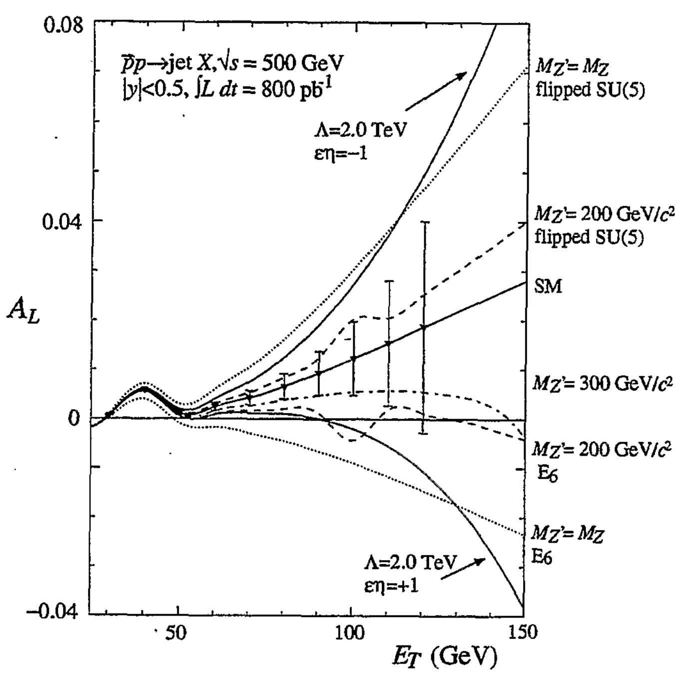
Using RHIC-Spin to find Physics beyond the SM ?

- suppose, we have a spin asymmetry that
  - ... we think we can predict rather precisely
  - ... is small within the standard model
- look for deviations from predicted asymmetry
- example : parity violations in jet production
  one beam longitudinally polarized

$$A_L^{PV} \equiv \frac{(d\sigma^{\leftarrow}/dE_T) - (d\sigma^{\rightarrow}/dE_T)}{(d\sigma^{\leftarrow}/dE_T) + (d\sigma^{\rightarrow}/dE_T)}$$

- in Standard Model, receives contributions from
  interference QCD $\times$ electroweak $\rightsquigarrow$ small

Bourrely, Guillet, Soffer; Tannenbaum; Taxil, Virey



· generic contact interaction:

$$\sim \frac{g^2}{\Lambda^2} \bar{\Psi}\Gamma_\mu\Psi \; \bar{\Psi}\Gamma^\mu\Psi$$

to be viable need :
large $\sqrt{S}$, high luminosity
precision in SM prediction
(Ellis,Moretti,Ross; WV)

Conclusions :

- we are still learning about the complex structure of the nucleon !
- spin fraction of quarks is small – what else will we find out ?
- new facilities – RHIC ! – will provide an inexhaustible wealth of information. Lepton-Hadron experiments will remain complementary and vital
- *very* exciting times ahead of us
- spin physics will continue to provide challenges for both theorists and experimentalists – a good time to get involved !

RHIC PHYSICS AND NEW FORMS OF MATTER

Larry McLerran
Brookhaven National Laboratory

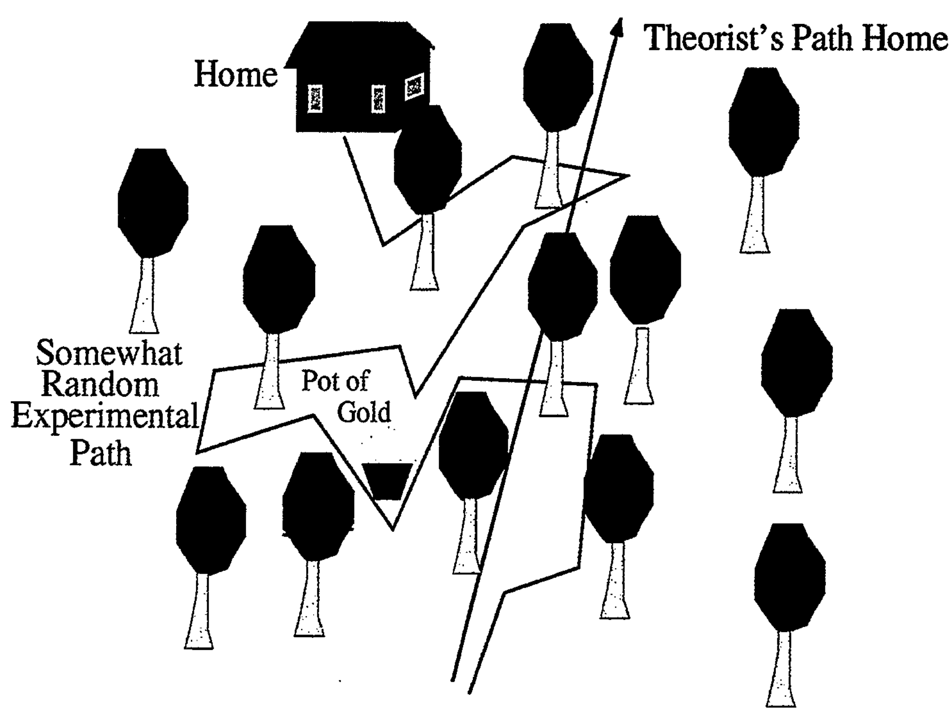
RHIC and New Forms of Matter

What are we trying to understand?

What have we learned?

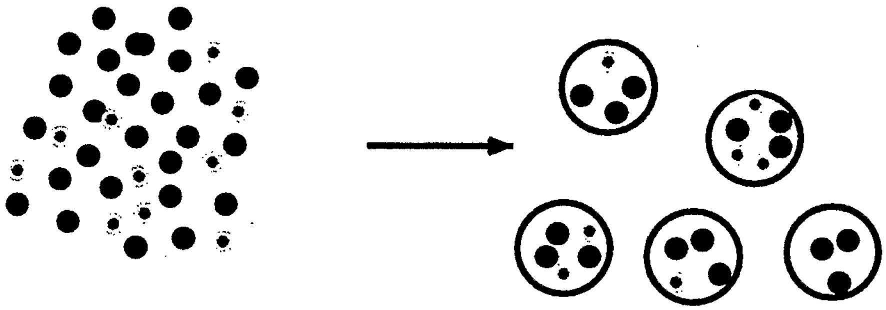
What do we expect to learn?

What do we hope to learn?



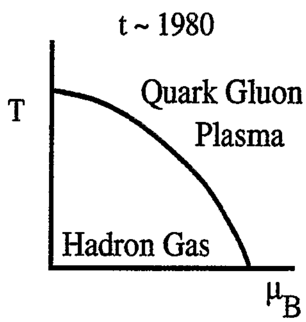
Kharzeev, Gribov

The Quark Gluon Plasma

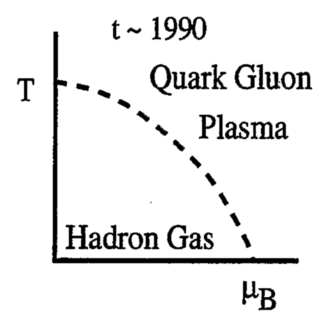


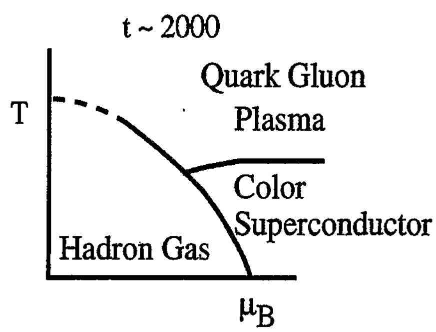
Ouark-Gluon Plasma ⟶ Hadron Gas

The Evolving QCD Phase Transition



Critical Temperature 150 - 200 MeV ($\mu_B = 0$)
Critical Density 1/2-2 Baryons/Fm^3 ($T = 0$)





Satz et .al.; Shuryak et. al., Wilczek et. al. .....

What have lattice simulations shown?

How do particles get their mass?
Why is the pion mass so small?
Are confinement and chiral restoration related?
How does linear potential arise?

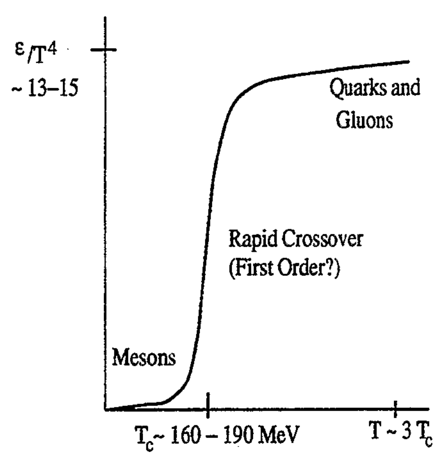
Deconfinement:

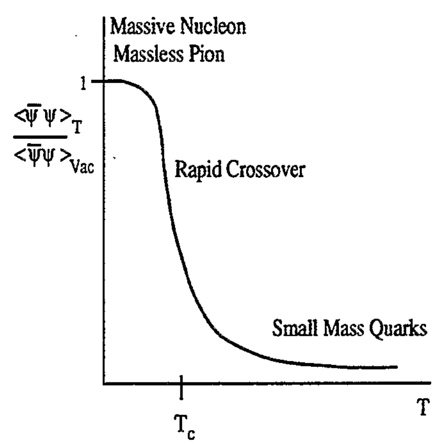
N_{dof} changes by order of magnitude.

Chiral Symmetry:

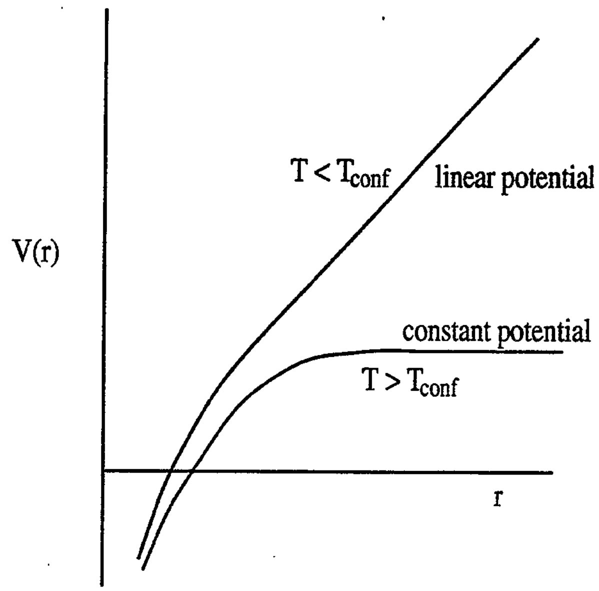
$m_{up}, m_{down} \sim 0$

$M_{nucleon} \sim 1\ GeV$

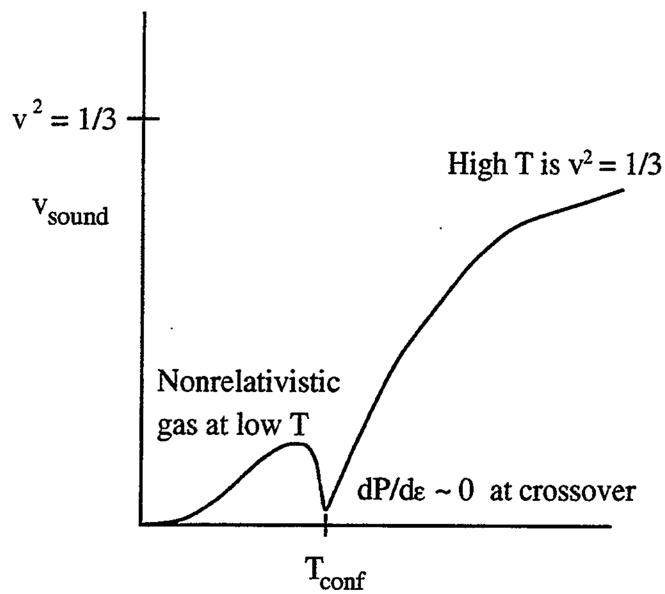




Is the confining force still linear for $T > T_{dec}$?



What is the equation of state? Sound velocity?

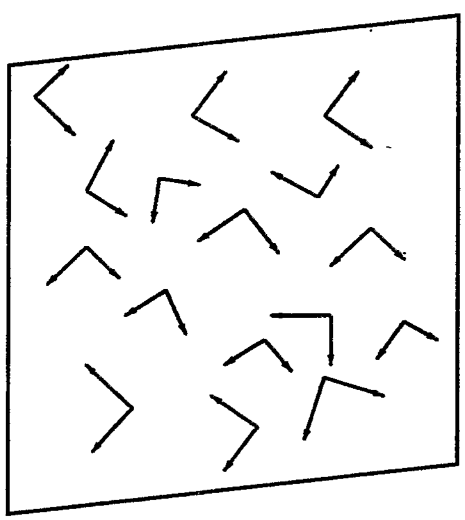


The Color Glass Condensate

Hadron in frame where it has
high momentum:

High momentum constituents generate
low momentum wee partons
Density of gluons per unit area
becomes large.
Fields random on thin sheet travelling
near speed of light

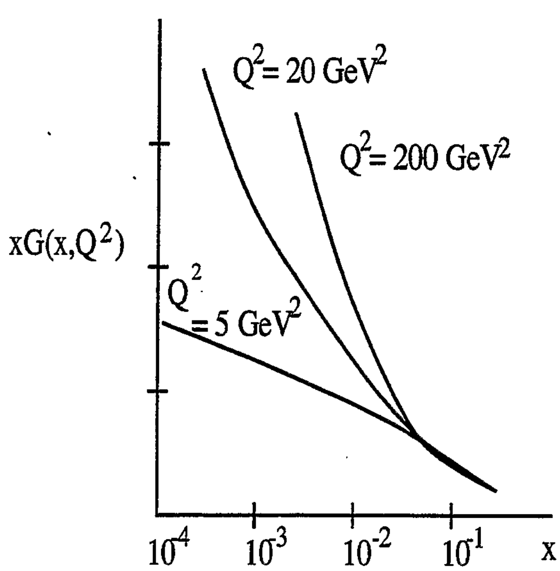
Gribov, Levin, Ryskin
Mueller, Qiu



Universal
high energy
behaviour
for all hadrons.

Jalilian–Marian, Kovner
Leonidov, Venugopalan
Weigert, Kovchegov
Iancu, Ferreiro, McLerran
Golec–Biernat, Wustof
Blaizot, Weideman, Balitsky

Color Glass Condensate and Saturation



Gribov, Levin, Ryskin;
Mueller, Qiu
McLerran, Venugopalan

Gluon phase space density per unit area:

$$\rho = \frac{1}{\pi R^2}\frac{dN}{dp_T^2}$$

until

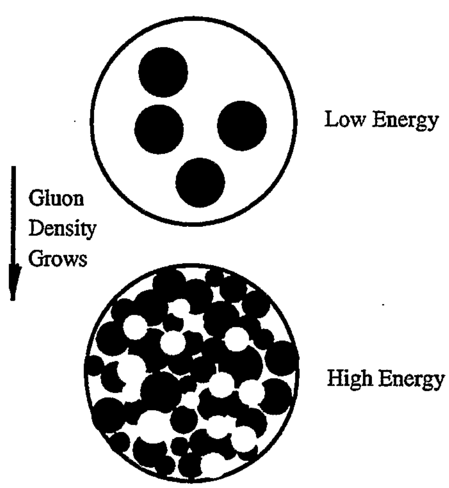
$$\rho \sim 1/\alpha_{strong}$$

$$Q_{sat}^2 \sim \int d^2k_T\ \rho$$

$$Q_{sat} >> \Lambda_{QCD}$$

implies

$$\alpha_{strong} << 1$$



Color Glass Condensate

Color: Made of Gluons

Glass: Wee fields (low momentum) are produced by higher momentum constituents. Time scales are Lorentz dilated compared to natural time scales.

Condensate: Gluon density biggest possible

Negative kinetic energy: ρ
Repulsive interactions: $\alpha\rho^2$
Compensate when $\rho \sim 1/\alpha_{strong}$.

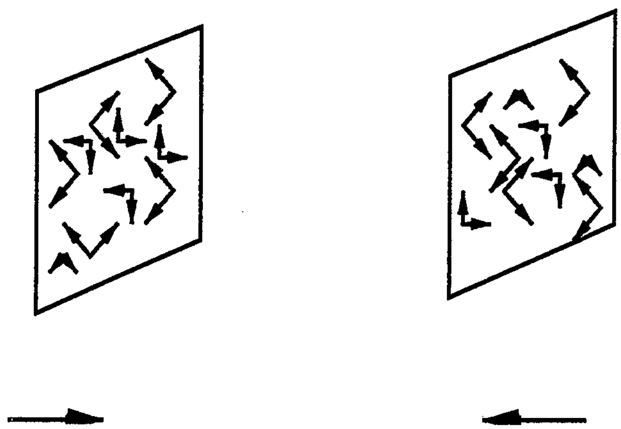
$1/\alpha$ is typical of Bose condensation.

Iancu, Leonidov and McLerran

Space–Time Evolution of Ultrarelativistic Nuclear Collisions

Kovner, Mclerran, Weigert

Krasnitz, Nara, Venugopalan



$t < 0$

Color Glass Condensate in each nucleus.

The Color Glass Condensate Melts into Quark Gluon Plasma

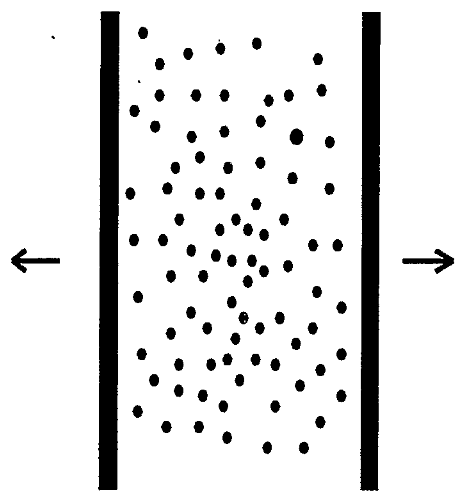
$t \sim 1/Q_{sat} \sim 0.3\ Fm$

at RHIC.

$\epsilon_{form} \sim Q_{sat}^4/\alpha_{strong} \sim 20 - 50\ GeV/Fm^3$

Space–Time Evolution of Ultrarelativistic Nuclear Collisions

Bjorken; Kogut, Susskind



Matter is formed with correlation between momentum and position due to Lorentz time dilation of the formation time.

Similar to Hubble expansion in Cosmology:

$N/V \sim 1/t$

If not equilibrated, $E/N \sim constant.$

If equilibrated, $E/N \sim T$, and $N/V \sim 1/t$

$T \sim 1/t^{1/3}$

$t_{form} \leq t \leq t_{therm}$

Matter thermalizes and Hubble expands.

$t_{therm} \sim 0.5 - 1\ Fm/c$

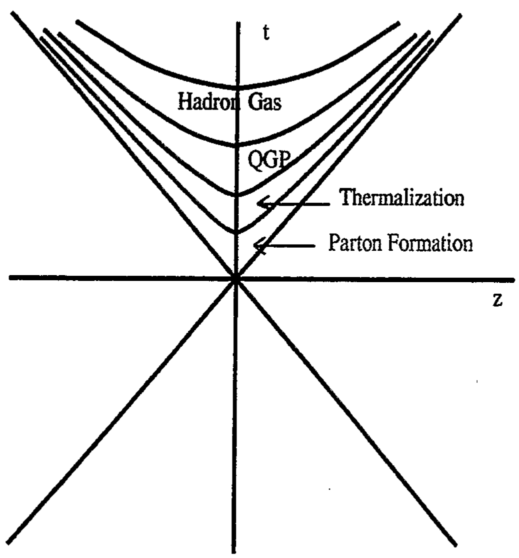
$t_{therm} \leq t \leq t_{decoupling}$

Matter expands as a thermal system.

$t_{decoupling} \sim R/V_s \sim 10\ Fm/c$

Space Time Evolution in Ultrarelativistic Nuclear Collisions

A vareity of time scales between thermalization and decoupling:



Kajantie
Ruuskanen
Eskola

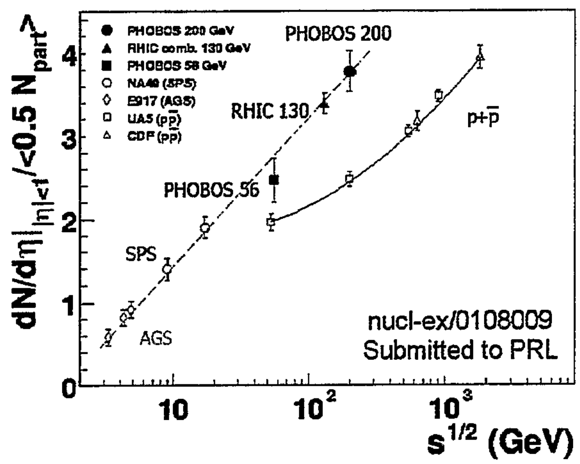
Can show the temperature always evolves slower than

$$T \sim t^{-v_s^2} \leq t^{-1/3}$$

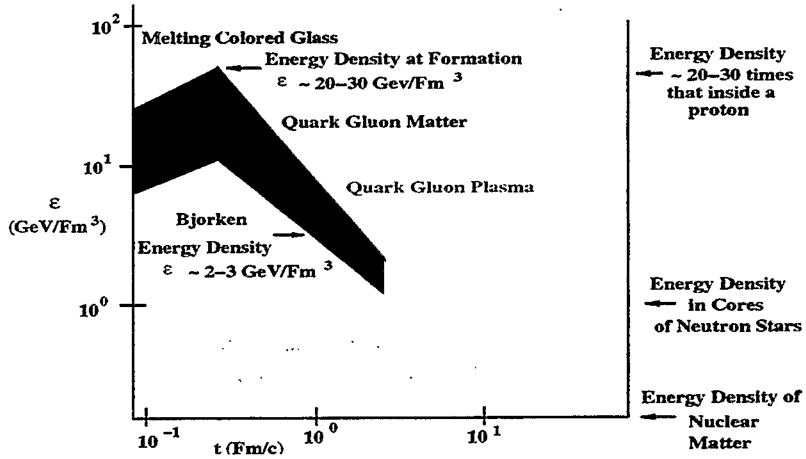
so long as t is smaller than the time at which the system becomes 3 dimensional.
At this time, the system begins to decouple.

What Have We Learned?

$dN_{ch}/d\eta|_{|\eta|<1}$ vs Energy



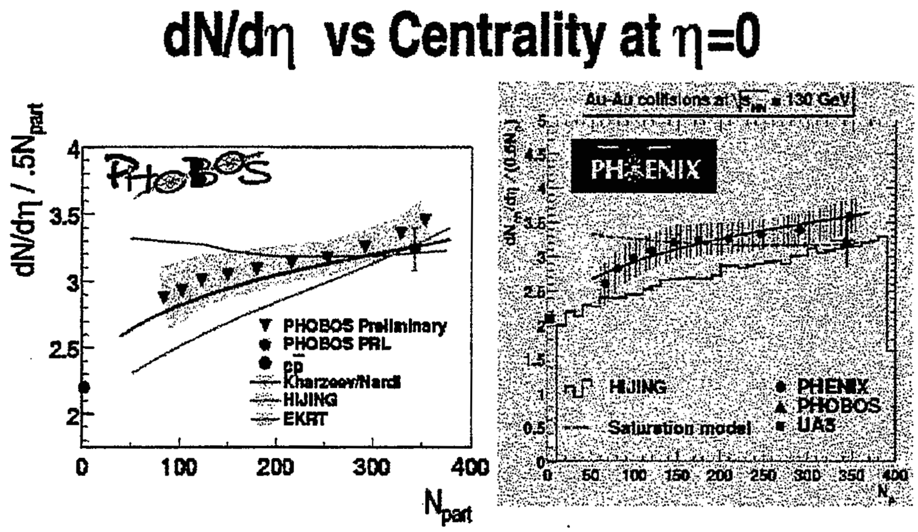
Bounds on Energy Density



Energy density too big for hadron gas!

What Have We Learned?

Gross properties of multiplicities consistent with Color Glass



Kharzeev and Nardi: $/dy \sim 1/\alpha_{strong}$

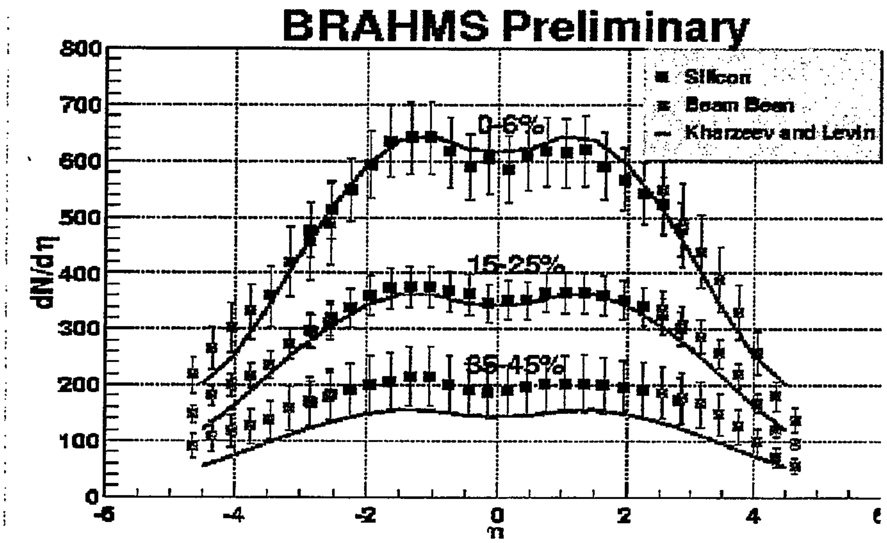
$\alpha(Q_{sat})$ depend on multiplicity per unit area.

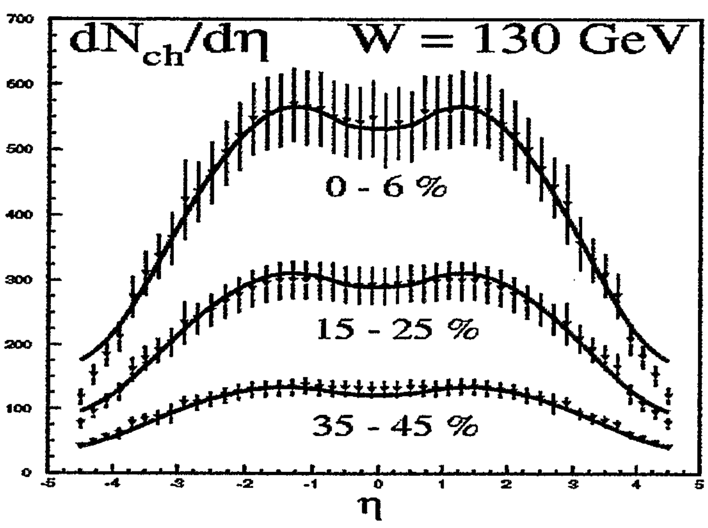
Kharzeev, Nardi and Levin: Rapidity density as function of y can be computed from Q_{sat}.

Q_{sat} is the only scale!

Kajantie, Eskola, Tuominen;
Kharzeev, Levin, Nardi

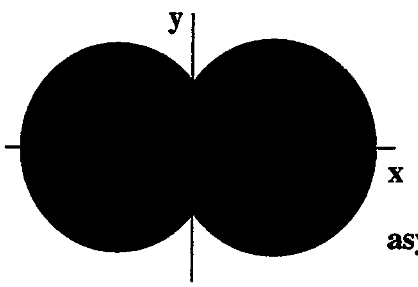
Gross Multiplicities Consistent with Color Glass



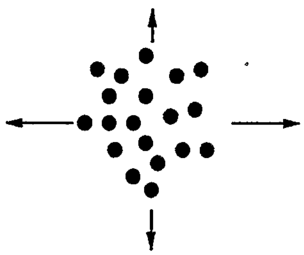


What Have We Learned?

It Is Matter and Interacts Strongly



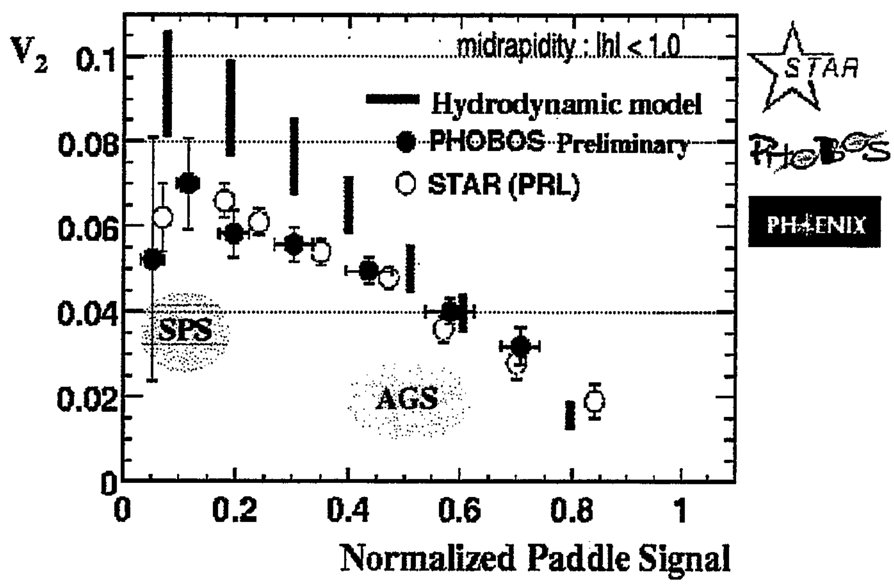
In region of overlap asymmetry of spatial distribution -> asymmetry of momentum distribution



$V_2 = <\cos(2\phi)>$ $\tan(\phi) = p_y/p_x$

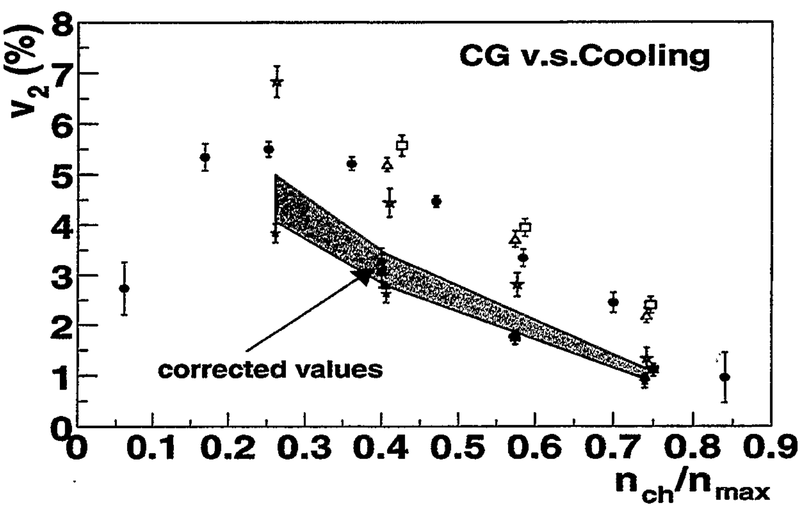
But is it Hydro?

Heinz, Kolb, Teaney, Shuryak; ...



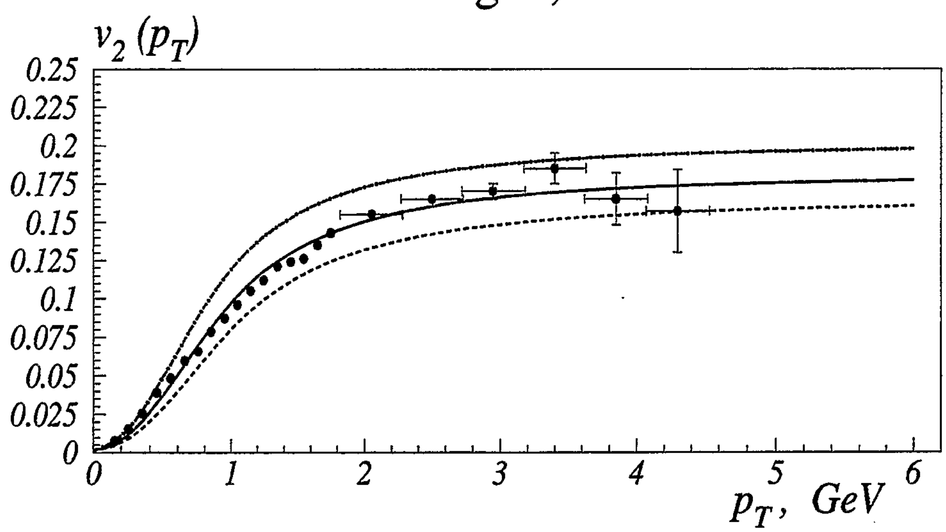
Or is it Color Glass Condensate?

Krasnitz, Nara, Venugopalan

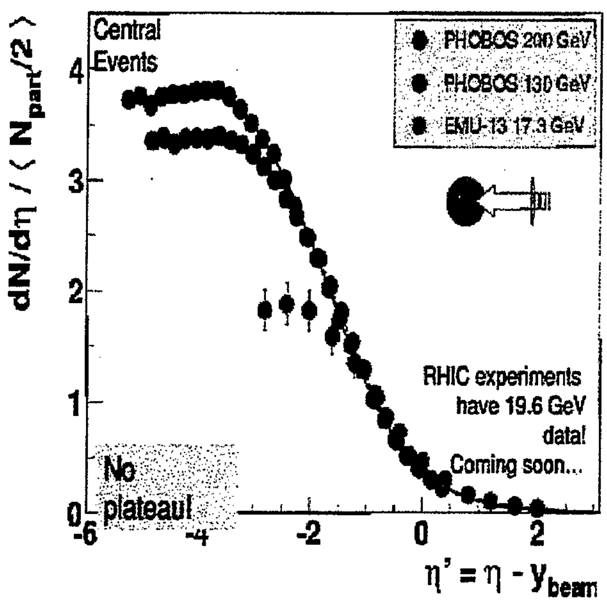


Or is it jets and saturation?

Kovchegov, Tuchin



Rapidity Distributions Consistent with Renormalization Group



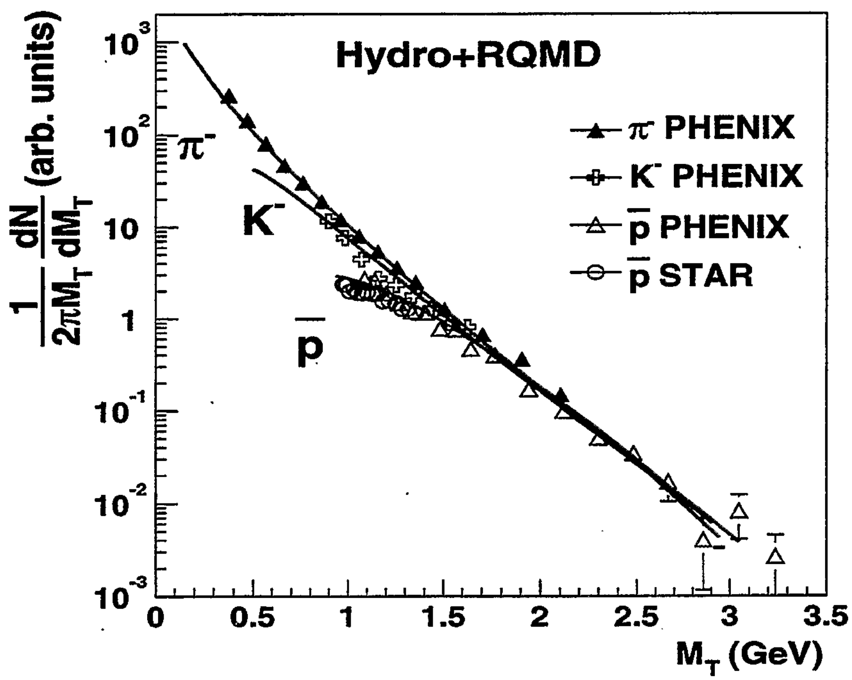
The effect of higher energy is to add on new degrees of freedom at small x.
The high x degrees of freedom are frozen!
Like renormalization group where the high momentum degrees of freedom are integrated out and absorbed into parameters of an effective Hamiltonian.

What Do We Expect to Learn?

Is there thermal equilibrium?

p_T distributions.

Teaney, Shuryak; Heinz, Kolb ....



At low to intermediate p_T hydro is consistent with data.

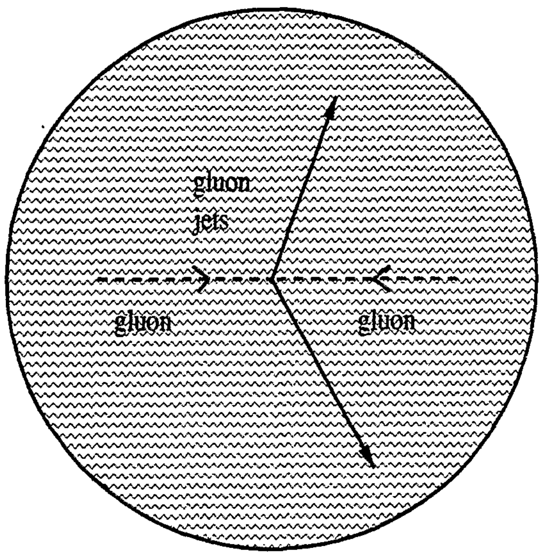
Data has m_T scaling, characteristic of hydro at large to intermediate p_T.

Shapes of ditributions seem consistent with hydro!

But at some p_T there must be jettiness.

What Do We Expect To Learn?

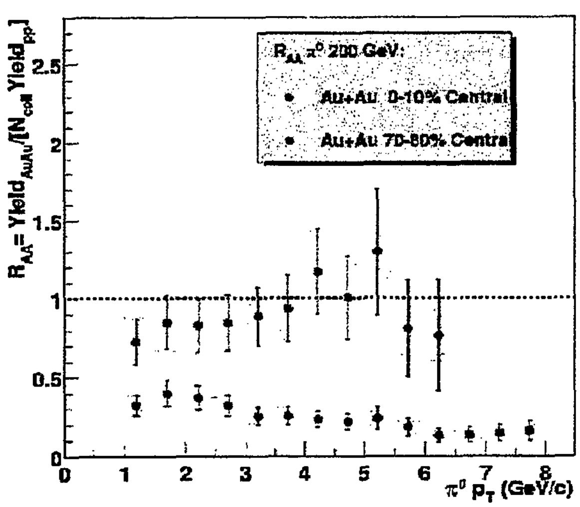
Is there thermal equilibrium?



Gluon jets produced in a medium will scatter on the media;

The high momentum component of the jet spectrum will be depleted.

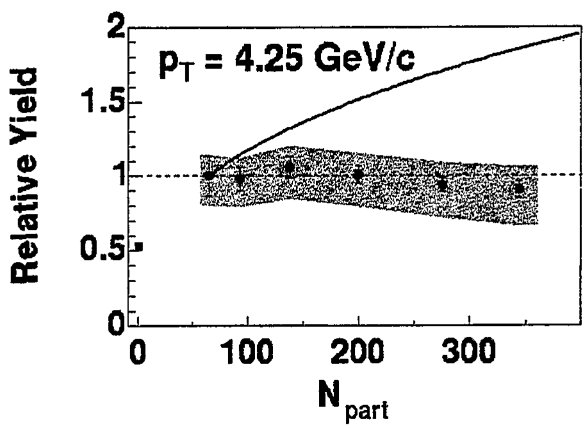
Mueller, Schiff
Dokshitzer, Baier
Peigne, Gyulassy
Wang



Is jet suppression due to parton energy loss?

What Do We Expect To Learn?

Or is jet quenching due to the
Color Glass Condensate?



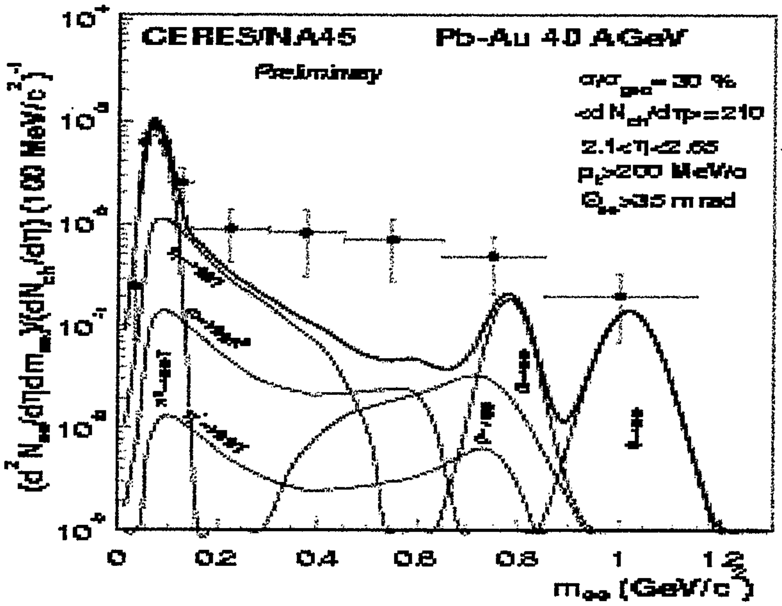
pA experiments crucial!

pA probes initial hadron wavefunction.
Next best thing to eA.

In frag. region of p, very small x of A.

Tuominen, Lenagahan; Jalilian–Marian, Dumitru
Levin, Tuchin, Kharzeev

What Do We Hope To Learn?



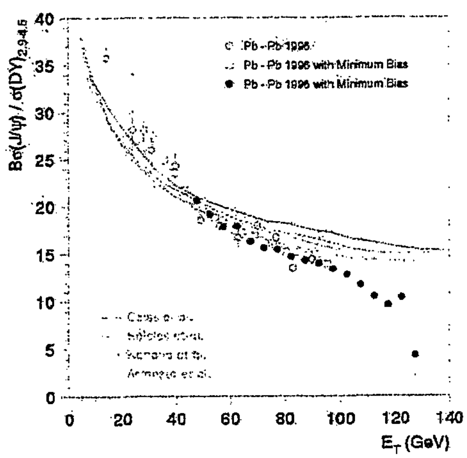
Does deconfinement occur in high density matter?
Does chiral symmetry restoration change masses?

Spectrum of low mass dileptons measured at CERN.
Probably resonance broadening
Rapp, Weise, Wambach.
Difficult at RHIC due to charm background.

Very difficult! but Rewarding!

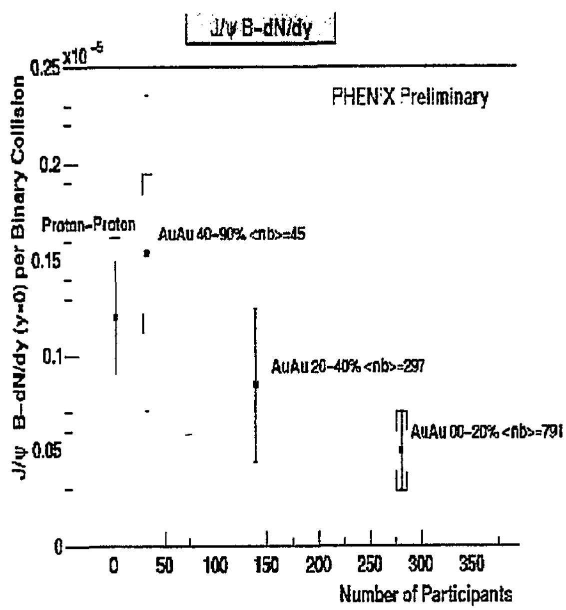
What Do We Hope To Learn?

Melting of the J/ψ



Is J/ψ suppression
due to hadronic scattering?
Changes in gluon distribution?
Higher twist effects?
Dconfinement?

Suppressors: Matsui, Satz
Kharzeev, Blaizot, Ollitrault
Enhancers: Rafelski, Thews
Stachel, Braun-Munzinger
Redlich, Gorenstein
Twister: Qiu
Rescatterer: Capella.

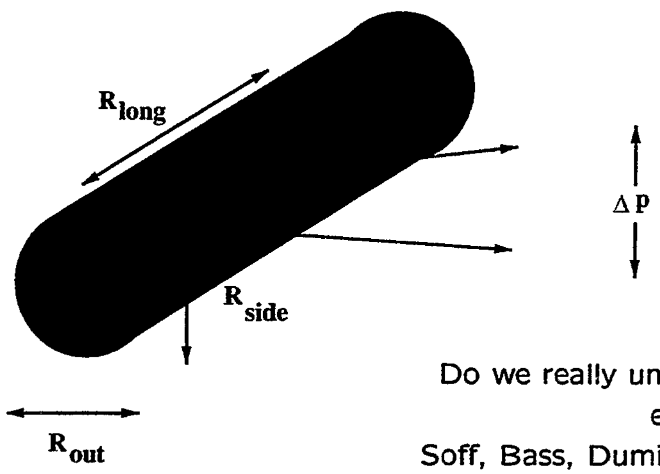


At RHIC energies
Does open charm increase
J/ψ by recombination?
Is J/ψ enhanced at RHIC?

Must measure open charm.
Must understand energy dependence.
Need pA and pp.

What Do We Hope To Learn?

Lifetime and Spatial Extent of Produced Matter

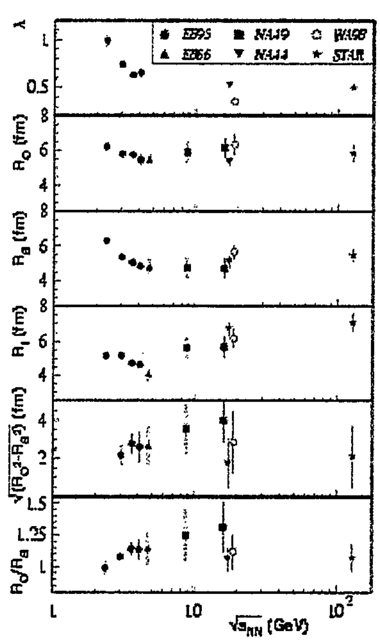


Difficult to interpret

R_{out}/R_{side}

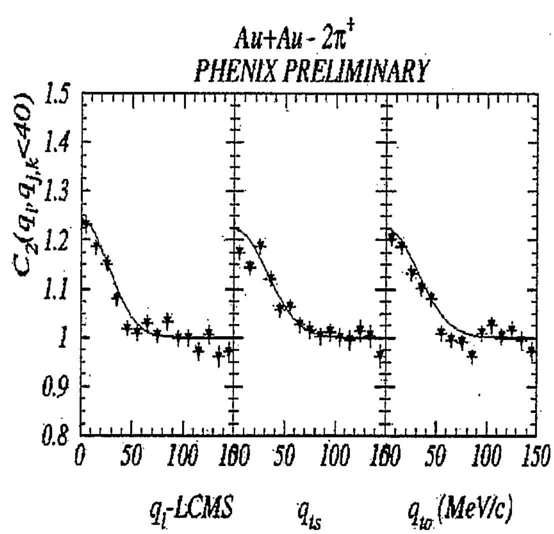
Problems with hydro?

Decoupling?



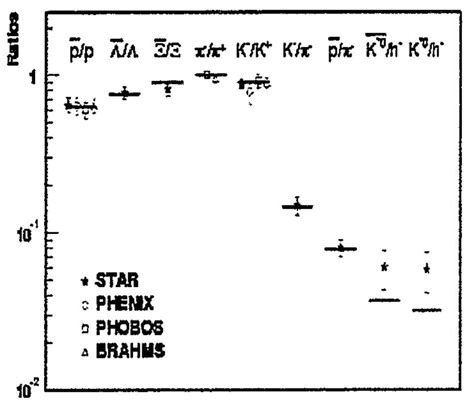
Do we really understand the space time evolution?

Soff, Bass, Dumitru, Heinz, Kolb, Teaney, Shuryak, Padula



What Do We Hope To Learn?

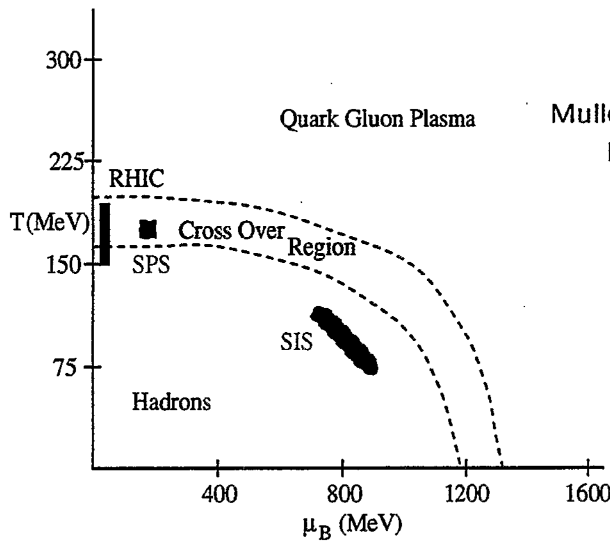
Flavor Composition of QGP



Can fit particle
abundances with temperature
and chemical potential
for baryon number
and strangeness.

It works too well!
e^+e^- collisions!

Are we not understanding
something fundamental and
universal?

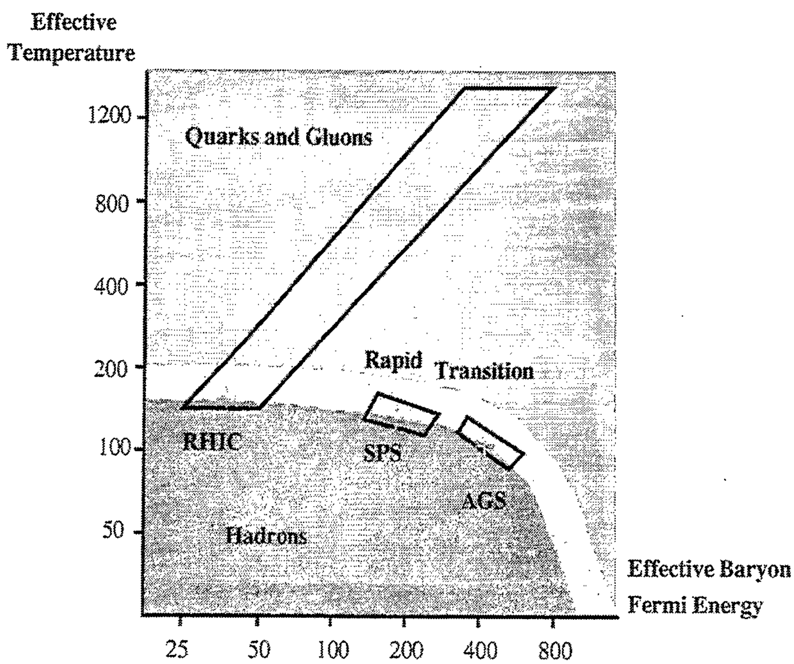


Muller, Rafelski, Cleymans, Redlich
Braun-Munzinger, Stachel,
Gorenstein, Gazdicki

Summary:

We have produced strongly interacting matter at energy densities do high it can only be reasonably described in terms of quarks and gluons.

We must now establish the properties of this matter.



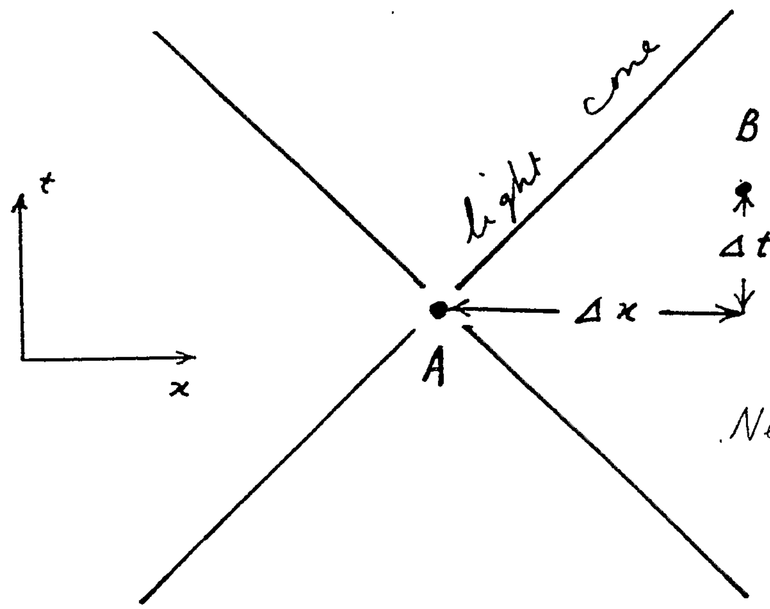
FUNDAMENTAL PHYSICS SHOULD BE BASED ON DIFFERENCE EQUATIONS

T. D. Lee
RBRC, CCAST, Columbia University

Fundamental Physics should be based on Difference Equations (not differential equations)

- Local field theory is inadequate
- **Both difference and differential equations can have the same continuous groups of sym. (including translations and rotations)**
- Difference equations have chaos and fractal type solutions, not possessed by differential equations
- **Differential equations are only approximations to difference equations**
- Physics should be described by difference equations, not differential equations.

two local measurements at A and B



$\hbar = c = 1$

Newton's Const. $G = l_P^2$

$\Delta t < \Delta x <$ Planck length $l_P \sim 10^{-33}$ cm

local field theory states that A and B are independent

But $\Delta E \sim \dfrac{1}{\Delta t} > \dfrac{1}{l_P}$

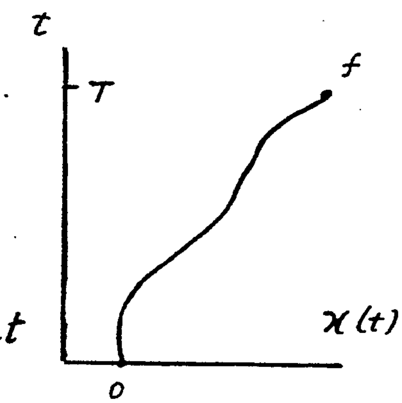
black hole horizon rad. $\sim G \Delta E > G \dfrac{1}{l_P}$

$\therefore$ " $> l_P > \Delta x$!

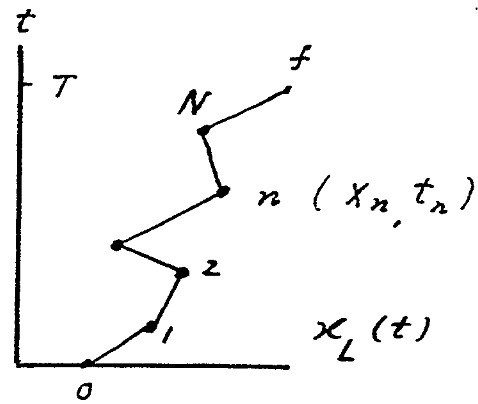
How can A & B be independent?

example : Classical Mech.

restrict



to



action $\quad A(x(t)) = \int \left[\frac{1}{2}\dot{x}^2 - V(x) \right] dt$

becomes $\quad A_L = A(x_L(t))$, $\quad \boxed{\frac{N}{T} \text{ fixed}}$

$\therefore$ time translational inv.

$$A_L = \sum_n \left\{ \frac{1}{2} \frac{(X_n - X_{n-1})^2}{t_n - t_{n-1}} - \frac{1}{2}\left[V(X_n) + V(X_{n-1}) \right] \cdot (t_n - t_{n-1}) \right\}$$

$\delta A_L = 0$ gives exact energy cons.

& momentum cons.

$$\frac{\partial A_L}{\partial x_n} = 0 \; : \qquad v_n - v_{n+1} = -\frac{1}{2}(t_{n-1} - t_{n+1}) \frac{\partial V(x_n)}{\partial X_n} .$$

where $\quad v_n = (X_n - X_{n-1})/(t_n - t_{n-1})$

$$\frac{\partial A_L}{\partial t_n} = 0 \; : \qquad E_n = \frac{1}{2} v_n^2 + \frac{1}{2}\left[V(x_n) + V(x_{n-1}) \right]$$

$$= E_{n+1}$$

General Relativity

$$A_S = \int_S \sqrt{|g|}\, R\, d^D x$$

S = arbitrary D-dim smooth manifold

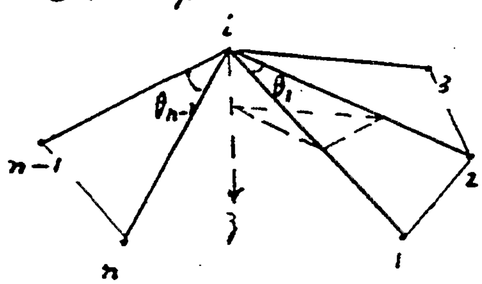
Discrete Gravity

Restrict S to L = D-dim continuous piecewise flat surface of D-simplices

$$A_L = \int_L \sqrt{|g|}\, R\, d^D x$$

Both A_L and A_S are inv. under $x_\mu \to x'_\mu$

example $D = 2$ Embed L in R_3



$R_3 = (x.y.z)$ space

Δ = 2 − simplex

$$A_L = \sum_i 2\epsilon_i$$

$$\epsilon_i = 2\pi - (\theta_1 + \theta_2 + \cdots + \theta_n)$$

= deficit angle

Embed L in R_N, $\min N = \begin{cases} 3 & D = 2 \\ 7 & 3 \\ 19 & 4 \end{cases}$

Thm For any L of D-dim

$$A_L = \int_L \sqrt{|g|}\, R\, d^D x = 2 \sum s\, \epsilon_s$$

(Regge Calculus)

s = vol of $D-2$ simplex

ϵ_s = deficit angle around s

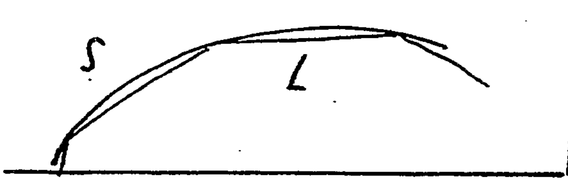
$D = 2$ $\quad A_L = 2 \sum_i \epsilon_i$ (Gauss-Bonnet)

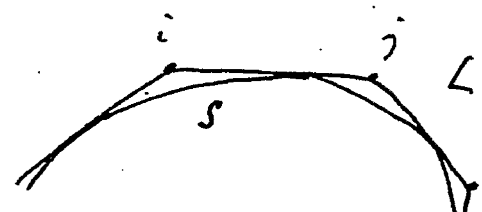
3 $\quad = 2 \sum_l l\, \epsilon_l$

(TDL and R. Friedberg)

4 $\quad = 2 \sum_\Delta \Delta\, \epsilon_\Delta$

Regge's idea	Discrete Gravity
Fix S	Fix L
vary $L \to S$	vary $S \to L$





Discrete gravity has <u>more</u> sym !

: Only $i = 1, 2, \ldots$ are real

DOMAIN WALL FERMIONS AND CHIRAL SYMMETRY

Taku Izubuchi
Kanazawa University, Japan
and
RIKEN BNL Research Center

Domain Wall Fermions

and

Chiral Symmetry

Taku Izubuchi (RBRC/Kanazawa Univ.)

Purposes of Dynamical lattice χ fermions

QCD physics beyond perturbative analysis

- CP violating matrix elements
  B_K, $\langle \bar{K} | H_{EW}^{\Delta S=2} | K \rangle$
  ϵ'/ϵ , $\langle \pi\pi | H_{EW}^{\Delta S=1} | K \rangle$,

- Structure functions / form factors
  $\langle P | \mathcal{O} | P \rangle$, $\langle \pi | \mathcal{O} | \pi \rangle$
- Matrix elements of Nucleon decay of GUT
  $\langle \pi | \mathcal{O}_{GUT} | P \rangle$
- Hadronic contribution to the muon $g-2$
- chiral Anomaly & Topology , η'
- Finite temperature/density, $T \neq 0$, $\mu \neq 0$

Use of chiral symmetry on lattice

- massless quark $q(x)$

$$S_f = \bar{q}\, \not{D} q = \bar{q}_L\, \not{D} q_L + \bar{q}_R\, \not{D} q_R$$

$$\text{symmetry:} \quad q_L \to e^{i\theta_L} q_L,\, q_R \to e^{i\theta_R} q_R$$

- Spontaneous breaking of chiral symmetry, $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$.
  NG boson, $M_\pi^2 \propto m_q$. The origin of constituent quark mass or proton.

- Fine tuning of fermion mass is unnecessary
  c.f. light Wilson Fermion $\delta M_W = -cg^2$, exceptional configurations

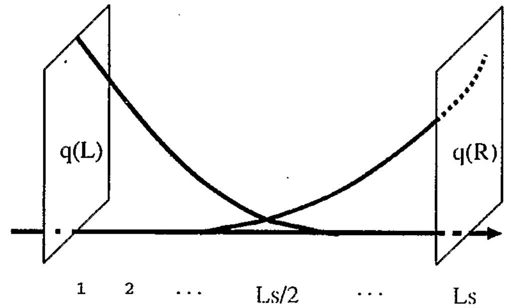
- discretization error should be small.(lattice spacing, $a > 0$)
  No local operator with dimension five with chiral symmetry.
  $\mathcal{L}_{lat} = Z\mathcal{L}_{cont.} + a^2 O_6 + \cdots$
  O(a) error is suppressed. Could use relatively large a to predict continuum limit

- unphysical operator mixing is prohibited by χ-sym
  c.f. B_K

$$\langle \bar{K} | (\bar{s}d)_{V-A} (\bar{s}d)_{V-A} | K \rangle \propto p_K p_{\bar{K}}$$

mixing with other $(\bar{s}\Gamma d)(\bar{s}\Gamma d)$. (Worse for $DeltaS = 2$ because of the $1/a^n$ divergent.)

Domain-Wall Fermions



$$\psi(x, s)$$

▷ x, y : *space-time*

▷ s, t : *5th coordinate (species)*

4-dim quarks at the boundary.

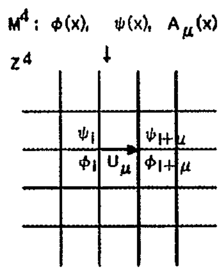
$$q(x) = P_- \psi(x, 1) + P_+ \psi(x, L_s)$$

$$\bar{q}(x) = \bar{\psi}(x, L_s) P_- + \bar{\psi}(x, 1) P_+$$

Chiral symmetry is preserved with a good accuracy: $\exp(-CL_s)$

Procedure of Lattice QCD

- 0. divide space time into lattice: lattice spacing a.



- 1. make QCD vacuum (configuration ensemble), $U_\mu^{(i)}(x), i = 1 \cdots O(100)$.
  physical input: $(\beta = 6/g^2, m_q)$ search in parameter space.
- 2. measure observable (e.g. hadron correlator) and take the ensemble average, $\langle \mathcal{O} \rangle = \sum_i O_{lat}^{(i)}$.
- 3. Renormalize. $O_{cont.}(\mu) = ZO_{lat}(a^{-1})$

  lattice spacing is determined from dimension-full quantity. e.g. $m_\rho a^{-1} =$ 770MeV.

Configuration generation

generate $U_\mu(x)$ according to QCD action

$$Prob[U_\mu(x)] \propto \exp(-S_{QCD})$$

- Quenched approximation: $\det(\not{D} + m) \rightarrow 1$
- Full QCD (with dynamical sea quark loop):
  $\Longrightarrow$ Hybrid Monte Carlo
  very expensive $\sim O$(1 year)

pathology of quenched approximation

Only valence quarks exist.

- lack of Unitarity
- $m_{\eta'} = m_\pi$, quark hairpin diagram, quenched chiral logs.
- a_0 scalar corelator loses positivity.
  (final state interaction of $K \rightarrow \pi\pi$)

Hybrid Monte Carlo

Fermion is not floating point numbers (Grassmannian).

- gauge link: $U_\mu(x) \sim e^{igaA_\mu(x)}$,
- Dirac operator: $D[U] \sim \not{\partial} + ig \not{A}$,
- $S_g \sim \int trF_{\mu\nu}^2$, $\qquad \det^2 D = \det D \det(\gamma_5 D \gamma_5) = \det(DD^\dagger)$

$$Z = \int \mathcal{D}U_\mu \det\left[DD^\dagger[U]\right]^{N_f/2} e^{-S_g}$$

- Psuedo fermion: $\Phi_F(x)$,
- conjugate momentum: $P_\mu(x)$ (Bosonic)

$$Z = \int \mathcal{D}[U_\mu \Phi_F P_\mu] \exp\left\{ -\sum^{N_f/2} \Phi_F^\dagger [DD^\dagger]^{-1} \Phi_F - \frac{1}{2} trP_\mu^2 - S_g \right\}$$

Canonical system (Φ_F: auxially field)

$$H(U_\mu, P_\mu) = \sum^{N_f/2} \Phi_F^\dagger \{D[U]^\dagger D[U]\}^{-1} \Phi_F - \frac{1}{2} tr P_\mu^2 - S_g$$

To update one configuration of the ensemble :

1. Refresh conjgate momentum $P_\mu(x)$:

$$Prob[P_\mu] \propto \exp(-TrP^2)$$

2. Generate auxially field $\Phi_F(x)$ by heat bath:

$$\Phi_F = D\eta, Prob(\eta) \propto \exp(-|\eta|^2) \rightarrow Prob(\Phi_F) \propto \exp(-\Phi_F^\dagger (DD^\dagger)^{-1} \Phi_F)$$

3. Molecular dynamics. proceed in fictitious time, τ $[U_\mu(x), P_\mu(x)]_{\tau=0} \longrightarrow [U_\mu(x), P_\mu(x)]_\tau$.

$$\frac{dU_\mu}{d\tau} = P_\mu, \qquad \frac{dP_\mu}{d\tau} = -\frac{\partial H}{\partial U_\mu}, \quad \text{(Force term)}$$

preserves Hamiltonian or weight, e^{-H}.

Done numerically ($\tau = N\delta\tau$) in the area preserving and reversible way (leap frog integrator)

4. Accept/reject to compensate the integrator:

$$Porb([U_\mu, P_\mu]_\tau) = \min\{1, \exp[\delta H]\}, \quad \delta H \propto \delta\tau^2$$

Dynamical DWF

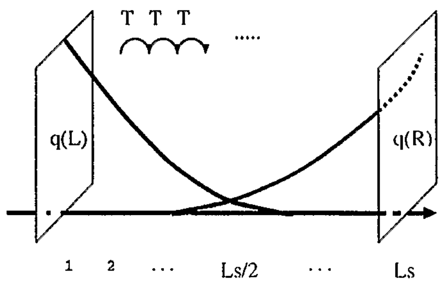
- using improved gauge action DBW2

  [QCD-TARO; Y.Aoki, K.Orginos Lattice 2001]
- using $H_W(-M_5)$ as a probe of m_{res} and $M_5(opt)$

- scale, a^{-1}, from matching of screening meson masses with dynamical staggered fermion on smaller lattice (deconfined phase)

- New algorithms
  - New force term. (C.Dawson, P.Vranas)
  - Chronological inverter [Brower, Ivanenko, Levi, Orginos]

Zero modes and χ sym. breaking



Axial Ward Takahashi identity

$$\partial_\mu \langle A_\mu(x)P(y)\rangle = 2m_f \langle P(x)P(y)\rangle + 2\langle J_{5q}(x)P(y)\rangle - 2\langle \bar{q}q(x)\rangle \delta_{x,y}$$

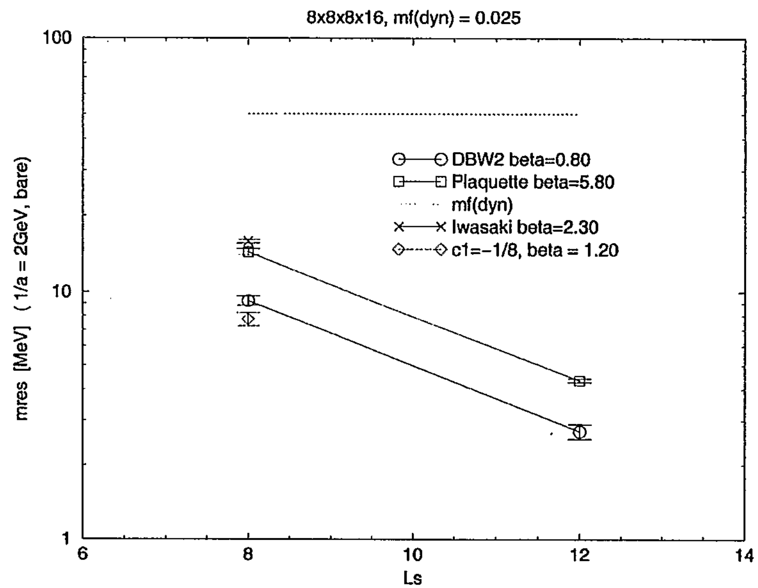
- non-local axial current $A_\mu(x)$
- explicit breaking operator, and residual mass m_{res}:

$$J_{5q}(x) = -\overline{\psi}(x,\frac{L_s}{2})P_L\psi(x,\frac{L_s}{2}+1) + \overline{\psi}(x,\frac{L_s}{2}+1)P_R\psi(x,\frac{L_s}{2}).$$

$$m_{res} = \frac{\langle J_{5q}(x)P(y)\rangle}{\langle P(x)P(y)\rangle}$$

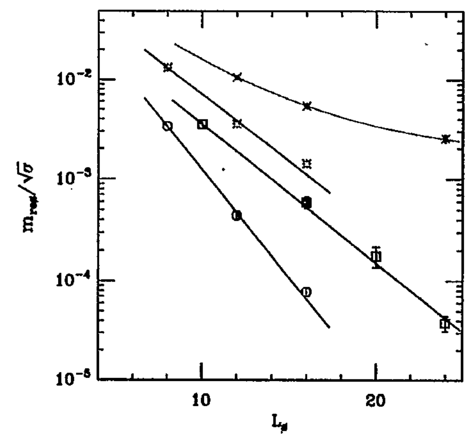
164

residual mass vs L_s

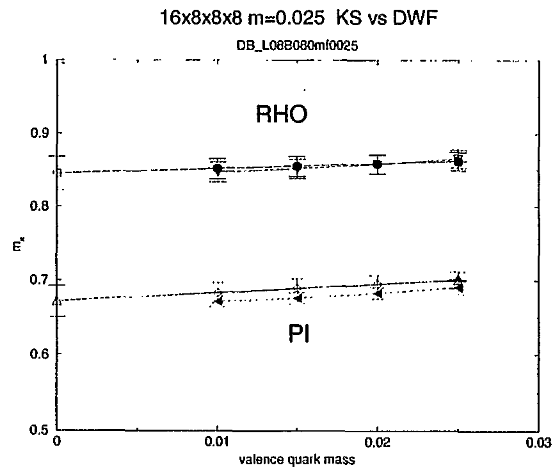


reasonable m_{res} for $L_s = 12$
rectangular action helps
(but less dramatically)

compared quenched cases:



[DBW2 + DWF] compared with [WilsonG + KS] ($T \neq 0$)



- $T \neq 0$, finite box, screening masses
- compared with ~ 2GeV dynamical staggered fermion
  (Xiaodong Liao)
  - ▷ *Wilson glue,* $\beta = 5.7$
  - ▷ *dynamical staggered:* $N_F = 2, m_f = 0.025$, *on* 16×8^3
- quark mass Z factor, Z_q, different scaling violation $\sim$ 20% at most (?)
- $T = a^{-1}/N_T \sim 250$ MeV